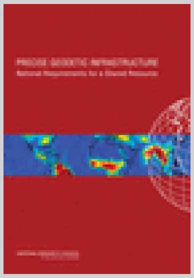

Precise Geodetic Infrastructure: National Requirements for a Shared Resource

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PRECISE GEODETIC INFRASTRUCTURE
National Requirements for a Shared Resource

Committee on the National Requirements for Precision Geodetic Infrastructure

Committee on Seismology and Geodynamics

Board on Earth Sciences and Resources

Division on Earth and Life Studies

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Preface

"Ubinam sum?"—where in the world am I?[1] This question—albeit a rhetorical one—sums up a central issue dealt with in this report. Since the advent of the space age, we have seen remarkable improvements in positioning, navigation, and timing of approximately one order of magnitude each decade with no indication that this rate of progress is abating. So we now know how to answer that question better than ever. This is the object of precise global geodesy. But the underlying infrastructure is at risk and its fragility a matter of serious concern.

The committee was asked to describe and assess the range of benefits to the nation that are dependent on high-precision geodetic networks, review high-priority scientific objectives that are dependent on geodetic networks, describe the infrastructure requirements for achieving these objectives and benefits, assess the opportunities for technological innovation that will arise from renewed investment in geodetic infrastructure, and recommend a national plan for the implementation of a precision geodetic infrastructure.

The committee gathered information from the scientific literature, numerous and extensive briefings by federal, academic, non-profit, and industry researchers, in addition to previous studies and reports. What seemed to us at the beginning to be a rather straightforward task was revealed to be a surprisingly complex one. This is because there seems to be no end to the list of scientific problems, technical endeavors, and societal activities that depend directly or indirectly on the global precise geodetic infrastructure. It was especially difficult to avoid duplicating the discussion of the Global Geodetic Observing System in the very complete volume edited by Plag and Pearlman (2009). We have restricted our focus to what we define in the report as "precise geodesy," that is, measuring the position of any point on the Earth with millimeter accuracy, variations in the length of the day to a few millionths of a second, the orientation of Earth's rotation axis in space to few billionths of a degree, and changes in the Earth's gravity to a few parts per billion.

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[1] Adapted from Cicero's exclamation in his Catiline orations: "Ubinam gentium sumus?"—Where on Earth are we? (Cic. *Cat. 1, 9)*

Our recommendations aim at maintaining and improving this capability, mitigating the risk of infrastructure degradation, and supporting a long-term sustainable national infrastructure capable of serving the full range of existing and future users.

The committee thanks the following individuals for making presentations and providing background material, figures, and other input: Greg Anderson, Yoaz Bar-Sever, Terry C. Bills, Yehuda Bock, Rich Brancato, Elbert "Joe" Friday, Tim Fuller-Rowell, Paul Gunderson, Philippe Hensel, Ken Johnston, Russ Kelz, Nancy King, John LaBrecque, Deborah Lawrence, William Leith, Chopo Ma, Zsolt Nagy, Steve Nerem, Ericos Pavlis, Nikolaos Pavlis, Jim Ray, Chris Rocken, Anthony Russo, Jim Slater, Dru Smith, Lucia Tsasoussi, Shimon Wdowinski, Neil Weston, Jim Whitcomb, and Bobby Williams.

The committee also thanks the staff of the National Research Council for their patient support of this project. In particular Courtney Gibbs and Nicholas Rogers provided essential logistics and computer help throughout. As study director, David Feary brought together the funding, secured the critical participation of agency representatives to the four meetings of the committee, and helped the committee assemble most of the raw material for this report. The committee is particularly grateful to NRC Post-doctoral Fellow Lea Shanley for her skillful and enthusiastic coordination of final efforts to bring this study to a successful conclusion.

J. Bernard Minster
Chair

Acknowledgments

This report was greatly enhanced by input from the many participants at the public committee meetings as well as from other contributors—Greg Anderson, Yoaz Bar-Sever, Yehuda Bock, Rich Brancato, Elbert "Joe" Friday, Tim Fuller-Rowell, Paul Gunderson, Philippe Hensel, Ken Johnston, Russ Kelz, Nancy King, John LaBrecque, Deborah Lawrence, William Leith, Chopo Ma, Steve Nerem, Ericos Pavlis, Nikolaos Pavlis, Jim Ray, Chris Rocken, Anthony Russo, Jim Slater, Dru Smith, Lucia Tsasoussi, Shimon Wdowinski, Neil Weston, Jim Whitcomb, and Bobby Williams. The presentations and the ensuing discussions helped set the stage for the committee's fruitful discussions in the sessions that followed.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report:

Véronique Dehant, Royal Observatory Belgium, Brussels
Timothy Dixon, University of Miami, Florida
Goran Ekstrom, Columbia University, New York
Gary Johnston, Geoscience Australia, Canberra
Rowena Lohman, Cornell University, Ithaca, New York
D. David Moyer, University of Wisconsin-Madison
R. Steven Nerem, University of Colorado, Boulder
Michael Pearlman, Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts
Michael Sideris, University of Calgary, Alberta, Canada
David Szymanski, Bentley University, Waltham, Massachusetts
Paul Tregoning, Australian National University, Canberra

Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by Michael Goodchild, University of California, Santa Barbara. Appointed by the NRC, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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APPENDIXES

Summary:
A Shared National Resource

A middle-aged rocky planet, Earth offers a wondrous combination of interconnected systems. From its molten core below to the ionosphere above, planetary layers interact dynamically, moving constantly, affecting climate and environment, and impacting life of all forms on the planet. Quantifying these changes is essential to understanding the underlying processes well enough to identify their root causes and to anticipate and respond to future changes. Precise global geodesy is an essential tool to capture these changes.

Geodesy is the science of accurately measuring and understanding three fundamental properties of Earth: its geometric shape, orientation in space, and gravity field, and the changes of these properties with time.[1] Over the past half century, the United States has been a world leader in the development of geodetic techniques and instrumentation. Today, these technologies enable scientists to determine the position of any point on the Earth with centimeter accuracy or better, to monitor variations in the time it takes the Earth to rotate around its spin axis with an accuracy of a few millionths of a second, to establish the orientation of Earth's rotation axis in space with an accuracy of few billionths of one degree, and to measure changes in the Earth's gravity that can perturb the position of an Earth-orbiting satellite by a few millionths of one meter. Geodetic observing systems provide a significant benefit to society in a wide array of military, research, civil, and commercial areas, including sea level change monitoring, autonomous navigation, tighter low flying routes for strategic aircraft, precision agriculture, civil surveying, earthquake monitoring, forest structural mapping and biomass estimation, and improved floodplain mapping (see Figure S.1 for a few examples of these applications).

In this report, the committee distinguishes between geodetic observing systems and geodetic infrastructure. Although these two overlap, they are distinguished by their primary purpose. When the report refers to geodetic observing systems (or in some cases geodetic observing networks), it is referring to systems that are designed to address specific goals (such as measuring sea level changes) and that may be used for a finite period of time. Geodetic infrastructure, on the other hand, supports

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[1] Geodesy is also closely related to the fields of navigation and surveying. In this report, however, the committee focuses on those aspects of geodesy requiring the highest precision.

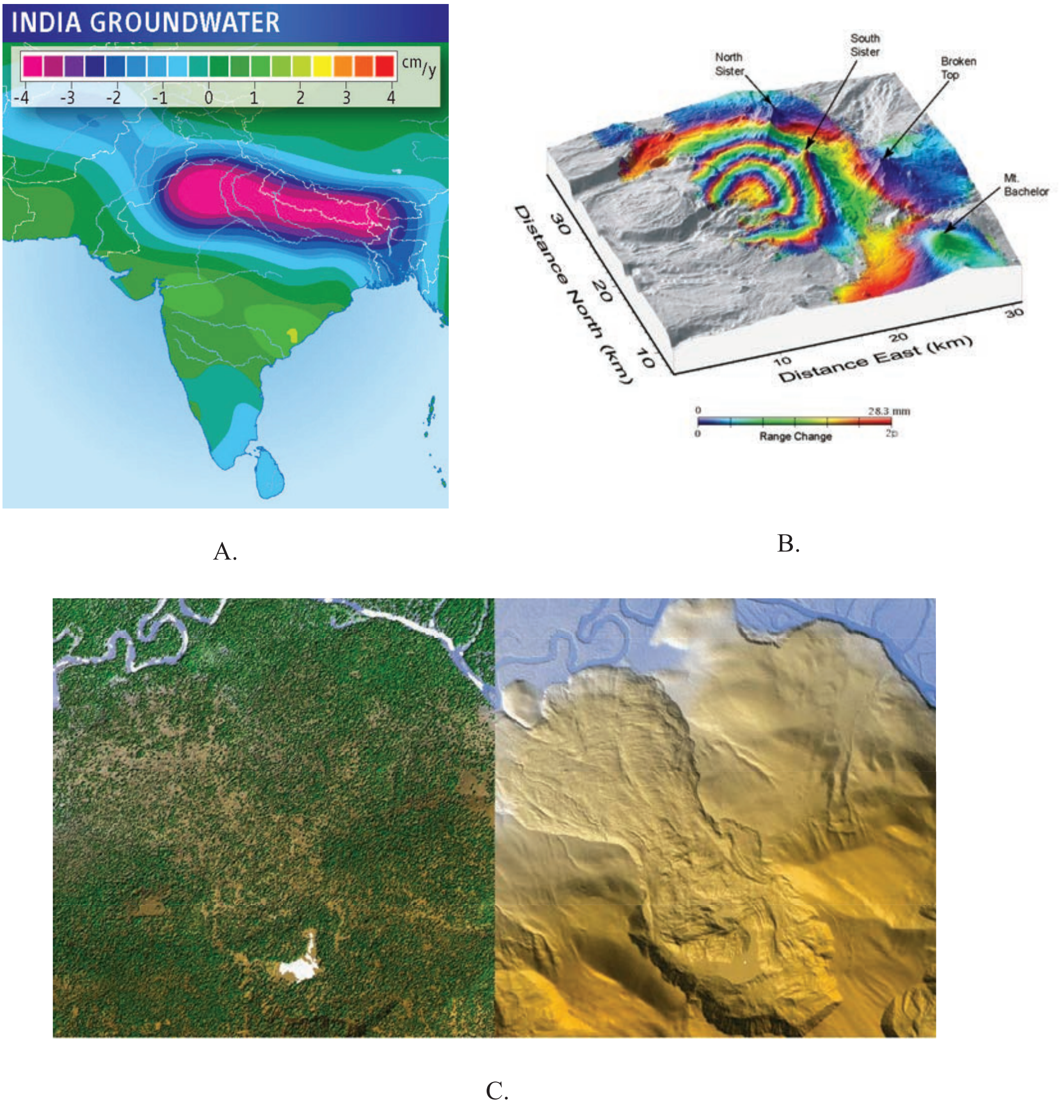

FIGURE S.1 The geodetic infrastructure supports many research and practical applications. For example, this infrastructure is critical to measuring: (A) Major groundwater depletion in India. (B) Uplift of the crust near the Three Sisters volcanoes, Oregon. (C) A landslide near Flathead Lake, Montana, revealed through the obscuring tree coverage using airborne LiDAR data collected by the NSF National Center for Airborne Laser Mapping (NCALM). These and other examples, as well as figure credits, are presented in Chapter 3.

all observing systems and applications over time; its main function is to provide the necessary information, such as the International Terrestrial Reference Frame (ITRF),[2] that underpins many Earth observation missions and location-based applications. The strength of the infrastructure lies in its

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[2] The International Terrestrial Reference Frame (ITRF) is a consistent set of agreed-upon 3-dimensional time-dependent coordinates for a network of reference points, distributed globally, which in turn are used to define the locations of all other sites. The DoD World Geodetic System 1984 (known as WGS-84) is consistent with the ITRF at the few-centimeter level, but the latter is intended for applications requiring the highest geodetic precision.

longevity, continuity, stability, robustness, accuracy, speed of accessibility, and capability for supporting innovation through the development of new observing systems that exploit the accuracy of the infrastructure. Geodetic observing systems therefore rely on the existence of the geodetic infrastructure to achieve their goals.

Recognizing the growing reliance of a wide range of scientific and societal endeavors on infrastructure for precise geodesy, and recognizing geodetic infrastructure as a shared national resource, the National Aeronautics and Space Administration (NASA), the U.S. Naval Observatory (USNO), the National Geospatial-Intelligence Agency (NGA) of the Department of Defense (DoD), the National Science Foundation (NSF), the National Geodetic Survey (NGS) of the National Oceanic and Atmospheric Administration (NOAA), and the U.S. Geological Survey (USGS) requested the National Research Council (NRC) to establish a committee to provide an independent assessment of the benefits provided by geodetic observations and networks, as well as a plan for the future development and support of the infrastructure needed to meet the demand for increasingly greater precision (Box S.1). In response to this charge, the committee made a series of focused recommendations in the body of this report for upgrading and improving specific elements of the infrastructure, for enhancing the role of the United States in international geodetic services, for evaluating the requirements for a geodetic workforce for the coming decades, and for providing national coordination and advocacy for the various agencies and organizations that contribute to the geodetic infrastructure. This summary provides a set of overarching recommendations that address Tasks 2 through 5, which are based on the analysis of information provided throughout the report. These follow from the committee's core recommendation:

> **Recommendation: The United States, to maintain leadership in industry and science, and as a matter of national security, should invest in maintaining and improving the geodetic infrastructure, through upgrades in network design and construction, modernization of current observing systems, deployment of improved multi-technique observing capabilities, and funding opportunities for research, analysis, and education in global geodesy.**

BOX S.1
Committee Charge

Improvements in positioning, navigation, and timing have always driven exploration and understanding of our world. Recognizing the national importance of maintaining and improving the global, high precision geodetic infrastructure that is fundamental to scientific discovery and leadership, and the applications to societal well-being and a vast array of commercial activity, the committee will:

1. describe and assess the range of benefits to the nation that are dependent on high precision geodetic networks;
2. review high priority scientific objectives that are dependent on geodetic networks;
3. describe the infrastructure requirements for achieving these objectives and benefits;
4. assess the opportunities for technological innovation that will arise from renewed investment in geodetic infrastructure; and
5. recommend a national plan for the implementation of a precision geodetic infrastructure.

GEODETIC INFRASTRUCTURE

The benefits of the geodetic infrastructure to society are profound and diverse, and this infrastructure has served the nation well by enabling the United States to establish a leadership position in commercial, civil, and scientific applications of geodesy. Many stakeholders depend on the geodetic infrastructure and contribute to it (see Table 1.1); these departments and agencies support a range of activities serving economic, scientific, and national security interests.[3]

Despite the reliance of many stakeholders on high-precision geodetic infrastructure, there is no formal governance structure or lead agency explicitly responsible for this infrastructure. Its many components have been developed separately, often to serve specific purposes rather than to support global applications, such as maintaining the ITRF. Increasingly, however, geodesists have found that using these different components in combination can strengthen and improve the accuracy of any specific observing system. Thus, as new observing systems come online, they are designed to depend on the existence of the underlying shared infrastructure.

In the broadest sense, the geodetic infrastructure includes a wide suite of ground-, air-, and space-based geodetic observing systems and their support structures; systems and standards for geodetic data analysis and combination; computational facilities and procedural structures for analysis and combination of global data sets; and archival and distribution systems for geodetic data and data products. This report focuses on the components of the geodetic infrastructure that contribute globally, in particular the four geodetic hardware systems and associated services that form the backbone of the ITRF. These four systems are Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR) and Lunar Laser Ranging (LLR), Global Navigational Satellite Systems (GNSS)/Global Positioning Systems (GPS), and Doppler Orbitography and Radio positioning Integrated by Satellite (DORIS). The United States developed and operates GPS, the most widely used global navigational system; France developed and operates DORIS; VLBI and SLR were developed and are operated in collaboration with a variety of international partners. Each system consists of a collection of sites equipped with hardware to determine and compile precise location information. Together these systems provide information about the Earth's short-term (daily and shorter) and long-term (years and longer) motions, and importantly, information required to establish and maintain the ITRF.

The data acquired by these infrastructure systems travel a long path (Figure S.2). The data from each system (dark blue box in Figure S.2) are analyzed (red box) to provide intermediate data products, which are then combined to yield the information (green) that can then be easily incorporated into other observing systems by users (cyan). Thus, at the lowest levels, these systems must be coordinated to ensure that there is complete consistency and that errors are not introduced at any stage. In fact, the global geodetic community has worked for decades to provide common standards for analysis and data formats for the precise *global* geodetic infrastructure, of which the U.S. sponsored geodetic infrastructure is a leading component.

The past decades have seen tremendous growth in the utilization of observations and methods that are dependent on the geodetic infrastructure for scientific and practical applications, and today many billions of dollars are invested in U.S. satellites and ground-based networks that rely on the high-precision geodetic infrastructure. The geodetic infrastructure, however, is currently operating far below its optimal state, both in terms of number of sites and in modernization of instrumentation. This report provides recommendations for modernizing the observing systems of the existing infrastructure to make them more robust. The most effective use of resources would be to upgrade existing sites, thereby maximizing the value of past investments and extending the contributions of existing sites to the long-term geodetic infrastructure.

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[3] This report does not attempt to address military applications of precise geodesy. However, it is clear that several government agencies with national security missions take advantage of the existence of the precise geodetic infrastructure to carry out their missions. Some of these applications are mentioned in this report.

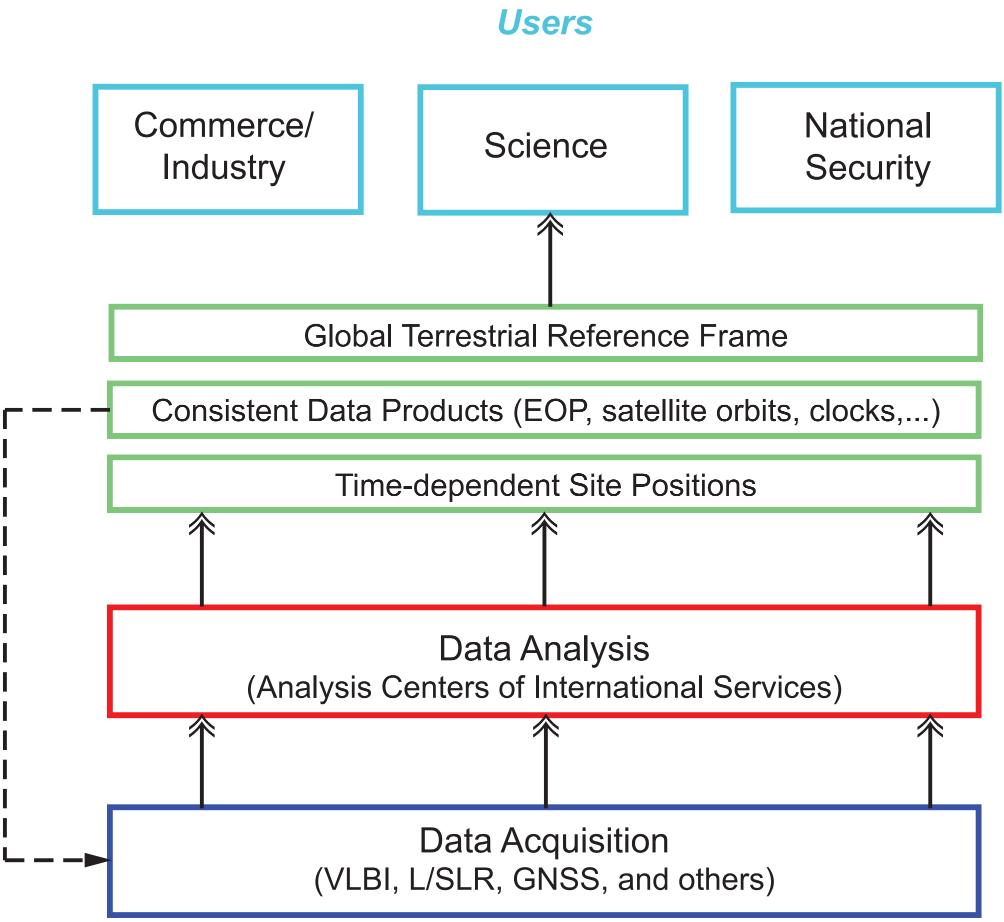

FIGURE S.2 The users of the geodetic infrastructure are organizationally removed from the systems that acquire the data. Raw data acquired by geodetic observing systems (described briefly in Chapter 1 and in some detail in Chapter 4) that form part of the geodetic infrastructure must first be analyzed in a consistent framework. This analysis is coordinated by international services and provides consistent precise data products, such as Earth-orientation parameters (rotational speed and direction of Earth's spin axis) and information on GNSS satellite orbits and clocks. The data products include technique-specific time-dependent site positions that are then combined to determine the ITRF (see Chapter 5), which serves as a standard reference. Once all these data products have been produced, they enable or facilitate a range of commercial and scientific applications (see Chapters 2 and 3).

Recommendation: In the near term, the United States should construct and deploy the next generation of automated high-repetition rate SLR tracking systems at the four current U.S. tracking sites: Haleakala, Hawaii; Monument Peak, California; Fort Davis, Texas; and Greenbelt, Maryland. It also should install the next-generation VLBI systems at the four U.S. VLBI sites: Greenbelt, Maryland; Fairbanks, Alaska; Kokee Park, Hawaii; and Fort Davis, Texas. Maintaining the long history of data provided by these sites is essential for reference frame stability as we transition between ever-evolving geodetic techniques.

The results of realistic simulations presented to the committee demonstrated that an increased densification of the global geodetic network to approximately 24 multi-technique or 'fundamental' stations could yield substantial improvements to the determination of the ITRF required to support the most demanding Earth science applications.

Recommendation: In the long term, the United States should deploy additional stations to complement and increase the density of the international geodetic network, in a co-operative effort with its international partners, with a goal of reaching a global geodetic network of at least 24 fundamental stations.

The committee also recognizes the importance of accurate gravity field measurements in support of space-based positioning techniques. Further, the proposed implementation of a national geoid-based[4] height system, consistent with global gravity models and accurate to 1-2 centimeters, requires strong support for gravity satellite missions and a revitalized U.S. terrestrial (ground and airborne) gravity program. Such a program also would support the multiple scientific and civil applications that call for monitoring changes in the gravity field over regional and global scales.

In addition, the committee identified many new applications that would benefit from a real-time GNSS/GPS data stream. These applications include autonomous navigation for land, sea, and air vehicles and robotic equipment; precision tracking of aircraft for laser and radar imaging; monitoring of space weather with potential to affect power grids, navigation, and communications; forecasting for extreme weather events; measurement of ground displacement in landslides; early warning systems for earthquakes and tsunamis; and monitoring of such critical structures as bridges, dams, railways, and pipelines.

Recommendation: The United States should establish and maintain a high-precision GNSS/GPS national network constructed to scientific specifications, capable of streaming high-rate data in real-time. All GNSS/GPS data from this network should be available in real-time without restrictions (and at no cost or a cost not exceeding the marginal cost of distribution), as well as in archived data files.

A GLOBAL COLLABORATION

With geodetic infrastructure deployed at sites around the Earth, modern geodesy is a global effort. This global infrastructure is organized by services of the International Association of Geodesy (IAG), including the International GNSS Service (IGS), the International VLBI Service (IVS), the International Laser Ranging Service (ILRS), International Gravity Field Service (IGFS), International Earth Rotation and Reference Systems Service (IERS), and the International DORIS Service (IDS). Each of these services archives data sets from a global network of stations, organizes and sets standards for data analysis, and distributes data sets and data analysis products without restrictions.

The United States plays a leading role in these services and benefits greatly from them. In effect, these services represent a force multiplier for the U.S. geodetic infrastructure. Playing a leading role enables the United States to exert a strong and lasting influence on standards and practices for the global geodetic network and data products.

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[4] Elevation is defined by the height of a point above the geoid, a reference surface (of constant gravitational potential) that approximates mean sea level. Extending the geoid to land was typically accomplished with ground-based leveling techniques but is now augmented with global gravity field models from space-based techniques. The International Association of Geodesy is initiating a pilot project for the definition and implementation of a unified geoid-based World Height System, but this issue, still under discussion, lies beyond the scope of this report.

> **Recommendation: The United States should continue to participate in and support the activities of the international geodetic services (IGS, ILRS, IVS, IDS, IGFS and IERS) by providing long-term support for the operation of geodetic stations around the world and by supporting the participation of U.S. investigators in the activities of these services.**

Specifically, a long-term national commitment to the primary global geodetic product—the International Terrestrial Reference Frame—would ensure continuity and stability of the reference frame, and the many geodetic observing systems that depend on it.

> **Recommendation: The United States, through the relevant federal agencies, should make a long-term commitment to maintain the International Terrestrial Reference Frame (ITRF) to ensure its continuity and stability. This commitment would provide a foundation for Earth system science, studies of global change, and a variety of societal and commercial applications.**

The committee also endorses the Global Geodetic Observing System (GGOS), a component of the Global Earth Observation System of Systems (GEOSS), being built under the aegis of the Group on Earth Observations (GEO), a voluntary partnership of governments and international organizations of which the United States is a leading member. GGOS links together existing and planned observing systems around the world and promotes common technical standards so that data from all these systems can be combined into coherent data sets. GGOS was conceived and introduced by the International Association of Geodesy as the new paradigm for sustained international cooperation toward integrating space-based geodetic techniques. The maintenance and development of the global precision geodetic infrastructure is recognized by GEO as a cross-cutting activity that affects many aspects of Earth science and the lives of most inhabitants of the planet.

A FOUNDATION FOR FUTURE GROWTH

The astonishing advances toward higher geodetic accuracy at increasing temporal resolution are made possible only by all components of the geodetic infrastructure working together as a coherent system. The components of the geodetic infrastructure, however, are dispersed among various departments, agencies, and organizations. Each of these bodies has independent missions and requirements, and there is no clear chain of responsibility and authority for maintaining, upgrading, and augmenting the geodetic infrastructure.

The nation's precise geodetic infrastructure has not been considered holistically before now. Nevertheless, the geodetic infrastructure is a shared asset that is required for the nation to maintain its global leadership in economic and scientific spheres and to sustain national security into the future. Cooperation between and within national agencies and international services is essential to ensure the long-term viability of the geodetic infrastructure. Fortunately, the discipline of geodesy offers a conceptual framework that has proven very successful on a global scale and that could be adapted to satisfy national needs.

> **Recommendation: The United States should establish a federal geodetic service to coordinate and facilitate the modernization and long-term operation of the national and global precise geodetic infrastructure to ensure convenient, rapid, and reliable access to**

consistent and accurate geodetic data and products by government, academic, commercial, and public users.

Establishing a federal geodetic service may not require the creation of a new independent agency, and it does not supersede the missions and strategic plans of the many agencies that currently support and rely on the geodetic infrastructure. Indeed, the federal geodetic service would support the missions of those agencies by drawing attention to the vital role of these otherwise separate and uncoordinated efforts. The unique mission of the federal geodetic service would be to ensure that the geodetic infrastructure meets the evolving future economic, scientific, and national security needs of the nation. It would achieve this mission by:

- maintaining, modernizing, and augmenting the geodetic infrastructure;
- coordinating the scientific and technical requirements and applications across stakeholders, including federal and state agencies, the scientific community, and commercial and public users;
- selecting a primary provider and clearinghouse agent for data products, such as raw instrumental data, tracking data, and the necessary metadata;
- coordinating the production and dissemination of data products, especially when the utilization of identical products by most or all end-users would be demonstrably beneficial or, in some instances, critical (for example, orbit information for precise navigation);
- supporting emerging geodetic technologies, such as geodetic imaging, and developing the associated tools and data sets to support these technologies;
- fostering fundamental research and education focused on technological and theoretical developments, ongoing deployments, and novel uses of precise global geodetic infrastructure; and
- functioning as the lead U.S. partner in the deployment of global infrastructure and international services.

The committee considered the role and function of the National Executive Committee on Space-Based Positioning, Navigation, and Timing (PNT). Although PNT delivers basic and essential administrative coordination at the national policy and agency level, it is not currently charged with coordinating activities at the data product level, nor is it charged with orchestrating the community to insure an orderly and effective development and promotion of data and data product standards. Thus, a federal geodetic service is needed to provide a centralized access point for accurate, consistent geodetic information for government, academic, and commercial users through state-of-the-art technology, such as internet portals.

This report discusses several possible approaches for implementing the federal geodetic service. These include: (1) assign to a *lead agency* the responsibility and the necessary resources to act as the federal geodetic service; (2) create an *embedded organization* that consolidates the federal geodetic service activities into a new organization within one of the existing agencies; or (3) create a *multi-agency federal service* based on the model of the international geodetic services. Because it would take advantage of the existing talent and expertise in federal and state government agencies, research organizations, academia, and industry, the federal geodetic service would require a small staff.

For this service to succeed and be sustainable, innovative, and flexible, it is imperative that its staff be steeped in state-of-the-art scientific research in precise global geodesy. For this purpose, all agencies that support scientific research in this field (for example, DoD, NASA, NOAA, NSF, and USGS) ideally would provide input to the strategic plan of the service. Periodic independent advice from other stakeholders in the public and private spheres and those operating at the local and global levels would ensure that the service continues to provide reliable access to accurate geodetic information.

Finally, the committee found that one of the "weakest links" in the implementation of a precision geodetic infrastructure was a lack of a trained workforce to develop and maintain the infrastructure in the coming decades. Skilled workers are needed to obtain the highest level of accuracy from the infrastructure, assess the capabilities of the infrastructure as it continues to evolve, and capitalize on advances in technology to improve the accuracy or decrease the cost of the infrastructure. Representatives from every federal agency interviewed by the committee raised concerns about a perceived growing deficit of well-trained space geodesists and engineers with this necessary knowledge. As a science, geodesy has long been a niche discipline, populated by a small group of experts. Agencies are finding it difficult to replace these highly skilled geodesists as they retire, and instead are forced to hire young professionals from other disciplines whom they must train on the job. Although the committee did not collect or analyze quantitative demographic data about the geodesy workforce, anecdotal evidence presented by the agencies brought this issue to the fore.

Recommendation: A quantitative assessment of the workforce required to support precise geodesy in the United States and the research and education programs in place at U.S. universities should be undertaken as part of a follow-up study focused on the long-term prospects of geodesy and its applications.

1

Where on Earth Am I Now?

To a sailor in the middle of the ocean or to a pilot above the clouds this question makes perfect sense, and a reliable answer to within a meter or so brings great comfort. With the development of intelligent transportation systems, passengers of vehicles on *terra firma* might pose the same question. It would seem that bridge builders or the operators of precise mining or agriculture machinery might not be so concerned, yet an answer accurate to a few centimeters is immensely valuable to them. It is rather less obvious why a geologist or a climate scientist would ask this very same question; but surprisingly, this is an even thornier issue for them, as they now require millimeter accuracy, both locally and globally. Only recently in human history has this age-old question become, on the one hand, an everyday practical issue and, on the other hand, a central scientific challenge. As our technologies have become more advanced, our need to know exactly where we are on Earth at any given moment has increased. As a result, innumerable activities of enormous economic and critical scientific value now depend directly or indirectly on the global, precise geodetic infrastructure.

The geodetic infrastructure in place today allows us to measure sea-level rise of a couple of millimeters a year; a shift in the center of the Earth by a tenth of a millimeter per year; changes in the length of the day of microseconds per day; and shifts in the position of the pole by fractions of a centimeter. Such highly precise measurements are critical to applications that monitor millimeter-scale deformation in the Earth's crust in earthquake-prone or active volcano areas; real-time navigation systems that position vehicles, ships, and airplanes to an accuracy of a few centimeters; systems that enable farmers to reliably plant two different crop seeds centimeters apart on the same field; mining machinery that operates automatically to an accuracy of a few centimeters; and unmanned aircraft that can fly anywhere on the planet to survey natural disaster areas, erupting volcanoes, or combat theaters.

Remarkably, our ability to calculate location and time ever more precisely has kept pace with the demand, improving by almost an order of magnitude per decade since the advent of the space age (Chao, 2003). This is no small task, however. Instead of being a rigid ball upon which reference lines could be drawn once and for all, the Earth changes shape continuously. The ground in the middle of continents moves up and down during the day by over 30 centimeters in response to lunar and solar tides; tectonic plates shift and collide; earthquakes and volcanoes disrupt the landscape by many meters; storms batter shorelines; ocean currents, hurricanes, and monsoons move enormous masses of air and water around the planet; and deep in the Earth's mantle and core, convection cells move continents and power the geodynamo, which generates our protective magnetic field. Instead of spinning smoothly and steadily like a well-balanced top, the Earth wobbles in complex ways, and its spin rate (and, as a result, the length of day) changes over time scales as short as hours, while slowing down over long periods of time.[1] To account for this continuous movement, we must continuously redraw the reference lines, and in turn continuously recalculate our position on Earth.

High-precision geodesy helps us to quantify and respond to local and regional problems by allowing us to "see" what we cannot sense directly. For example, the depletion of underground aquifers or oil and gas reserves can cause local subsidence, or sinking of the land, disrupting sewers and other underground utilities. On a much larger scale, geodesy enables us to monitor global climate change as it is reflected in ice sheet melting and sea level change. These trends, which only can be measured precisely with geodesy, ultimately may have significant—or potentially catastrophic—impacts, causing loss of life and billions of dollars of damage to homes, businesses, and the environment.

WHAT IS THE GLOBAL PRECISE GEODETIC INFRASTRUCTURE?

Geodesy is the science of measuring and understanding three fundamental parameters of the Earth—its shape, rotation and orientation, and gravity field—and their change over time. These parameters carry fundamental information about the planet and its workings. Today this is no longer a three-dimensional problem, but really a four-dimensional problem in which temporal changes in these quantities are tracked. Geodesists do this using an infrastructure based on precisely located positions of a set of reference ("fiducial") points on the Earth's surface. Using these reference points, geodesists create a *terrestrial reference system (or spatial reference system)*—a common coordinate framework for which scientists have determined, by calculation, all the reference points' exact coordinates at a given time. The primary realization of the global spatial reference system is the International Terrestrial Reference Frame (ITRF). The ITRF and other terrestrial reference frames are established by equipping selected reference points with some combination of radio telescopes, laser ranging systems, Global Navigational Satellite Systems receivers (GNSS, a general term for systems like the Global Positioning System, or GPS) and radio beacons, and sometimes gravimeters. In addition, data from observations of Earth-orbiting satellites, the moon, and distant extragalactic objects known as quasars are incorporated. This combination of ground-based instruments and satellites constitutes the precise, global geodetic infrastructure.

A common spatial reference frame is both an important theoretical concept and a practical tool. Using *geopositioning*, one can locate a point or an object as it moves within a terrestrial reference frame. Beyond navigation, the ability to track the real-time location of mobile devices equipped with built-in GNSS/GPS receivers has sparked rapid growth in location-based services. Utility companies, for example, equip field crews with smart phones, enabling real-time access to dynamic maps of underground cables and pipes that can be updated "on the fly" as workers move around a field site. Developments in location-based services may drive revenues of more than $12.7 billion by 2014, according to a report published by Juniper Research (Wauters, 2010). The accuracy of geopositioning, and the scientific and societal applications that rely on it, depend on the continued existence of a reliable technological and scientific infrastructure.

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[1] Keeping time of day, measured by the rotation of the Earth relative to the Sun, synchronized with more accurate atomic clocks is the reason for introducing the occasional "leap second."

THE VALUE OF PRECISE MEASUREMENTS

The power of modern geodesy is matched by the challenges it faces, namely, detecting minute changes in Earth's system over time. Over the past 50 years, space-based geodetic technologies have revolutionized the way we look at our planet, allowing us to measure and monitor changes in the Earth's system with unprecedented levels of accuracy and detail. Modern geodesy delivers precision to one part per billion, and precision of one part per trillion can be envisioned in the foreseeable future (see Box 1.1). The current level of precision enables us to track the shrinking distance between Los Angeles and San Francisco to an accuracy of 1 millimeter as we keep watch for the next California earthquake; or a millimeter shift of the pole associated with a large earthquake in Chile; or a microsecond change in the length of day associated with an Asian monsoon; or the slight change in the gravity field due to a drought-induced drop in the water table across the Mississippi drainage basin.

Such exquisitely precise measurements provide critical information for many areas of science with a tangible societal impact. One particularly complex example is sea level change. Over the past decade, the global sea level has increased by an average of 3.3 millimeters per year and has been predicted to rise by as much as one meter by the end of the 21st century. The shallow slope of some shorelines will exacerbate the impact of this vertical change in sea level, so that one meter of sea level rise would flood 2.2 million square kilometers of coastline, displace 145 million people worldwide, and result in the loss of $944 billion in combined global gross domestic product (Anthoff, 2006) (see Figure 1.1).

Geodetic technologies have been critical to measuring past sea level change over time, but predicting future changes can be exceedingly complex, underlining the need for precision infrastructure for global sea level monitoring. Global sea level change is largely caused by two factors: (1) changes in the thermal and salinity conditions of the ocean (which result from the expansion of the ocean's volume due to heating), and (2) flow of water into the ocean from melting ice sheets and glaciers. The combined measurements obtained from three geodetic observing systems—altimetry and gravity satellite missions, and tide gauge networks—allow us to estimate the contributions of these sources. Recent measurements indicate that melting of glaciers and polar ice sheets contribute approximately 2 millimeters per year to sea level rise. In the year 2007 alone, the Greenland ice sheet lost nearly 300 billion tons of its mass, enough to bury the District of Columbia under a mountain of ice nearly 2,000 meters high (about 6,500 feet), or blanket the entire state of California with three-quarters of a meter (2.5 feet) of ice. The west Antarctic ice sheet is melting at a comparable rate, and the Antarctic continent as a whole is undergoing changes that we will not fully grasp until the comple-

BOX 1.1
Precision Notation

Geodesists often use a "parts-per" shorthand notation to denote precision; this is the error in measurement of the distance between two points divided by the distance. For example, if the distance between two points separated by 1,000 km (1 billion millimeters) can be measured with a precision of 1 millimeter, then in "parts-per" notation the precision is 1 part-per-billion (e.g., Davis et al., 1988).

Distance		1 km	100 km	1,000 km
Precision	1 part per million	1 mm error	0.1 m error	1 m error
	1 part per billion	0.001 mm error	0.1 mm error	1 mm error

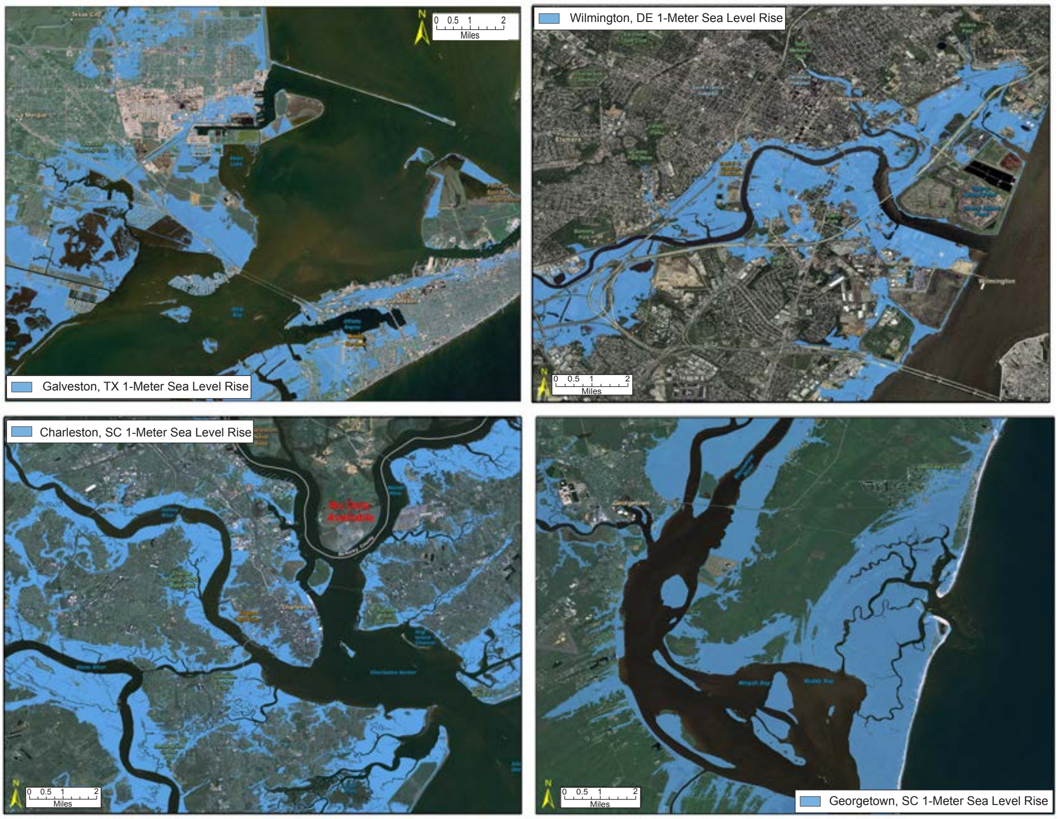

FIGURE 1.1 The potential flooding in coastal areas resulting from a potential sea level rise of one meter was mapped on either Mean High Water (MHW) or Mean Higher High Water (MHHW) depending on location (see Glossary for definitions). The sea level rise scenarios represent daily impacts at high tide, or the maximum extent of inundation. One meter of sea level rise by the year 2100 is a conservative estimate from the Intergovernmental Panel on Climate Change that is considered plausible (Rahmstorff et al., 2007). Geographic Information System (GIS) and spatial analyses were used to construct the projections; maps show the scale of potential flooding, but not the exact location, do not account for erosion or subsidence, and assume no wind, rainfall, or future construction. Model improvements for all these factors are possible, and would lead to improved forecasting and mitigation. All mapping was completed on the best available elevation data available to the Coastal Services Center. SOURCE: Courtesy of the NOAA Coastal Services Center.

tion of current and future satellite missions, part of the “decadal survey” list (NRC, 2007a). In this report, we examine the 0.6 millimeter per year error budget that the current geodetic infrastructure affords us. The combination of direct geometric measurements of sea-level, ice-sheet, and sea-ice changes (from ocean radar altimetry, ice-sheet laser altimetry, tide gauges, and other geodetic station elevations), and unprecedented mass change estimates (from satellite-based monthly gravity solutions) gives us unique and essential limits on climate dynamics models.

Although ice sheet melting causes global sea level rise—seven meters for a hypothetical total melting of Greenland and 3–5 meters for total collapse of West Antarctica—it also leads to significant regional variability. Counter-intuitively, the shedding of ice from a frozen continent can lead to a local lowering of sea level relative to the land near the disappearing ice sheet. This is because the removal of the ice load causes the ground to rebound upward, while at the same time the gravitational attraction of the ice mass that used to pile up ocean water around the ice sheet is no longer there, so the water level drops locally. The detailed geographic pattern of relative sea level change is therefore a complex, but critical, piece of information in interpreting the causes—and preparing for the impacts—of climate change. Because of such complications, the geography of sea level rise caused by melting of the Antarctic and Greenland ice sheets is not accurately predicted. If the Greenland ice sheet should melt altogether, then the east coast of the United States would experience sea level rise, but England would initially see a sea level drop. If, on the other hand, the west Antarctic ice sheet melts, then Washington, DC, would have to contend with a local rise in sea-level of about 30 percent greater than the global average (Bamber et al. 2009; Mitrovica et al., 2009). This underscores how complex the impacts of an ice sheet collapse can be, and the need for precise monitoring of the Earth's response to surface loads.

As this example illustrates, improvements in measurement precision have pushed geodesy beyond its traditional disciplinary boundaries and into research domains such as climate and atmospheric science, oceanography, hydrology, geology, seismology, geodynamics, geology, and glaciology. Geodetic observations of changes in the Earth's shape, rotation, and gravity field offer new and unique insights into dynamic processes and mass transport in the Earth system, such as ice melting, sea level rise, land subsidence, and aquifer depletion. In addition, geodesy provides the foundation for most other Earth observations, and for a wide array of applications with broad societal and commercial impact—from early warning systems for hazards to location-based services. Unfortunately, the scientific infrastructure dedicated to geodetic observations has become fragile as a consequence of aging components, lack of redundancy with single-point-of-failure designs, and ongoing fiscal pressures on operations and maintenance budgets. Degradation of the geodetic infrastructure could lead to gaps in critical observations that are needed to test the validity of models for ice dynamics, sea level rise, and climate change. This report assesses the scientific and societal requirements for precise geodetic observations and offers options for the support of a sustainable national geodetic infrastructure capable of serving the full range of existing and future users.

COMMITTEE CHARGE AND APPROACH

This report is one of several undertaken by the National Research Council (NRC) examining the need for precise geodetic observations.[2] The report *Geodesy in the Year 2000* (NRC, 1990) identified many areas of science that would benefit from improvements in the accuracy of geodetic measurements and emphasized the need for continuity of geodetic measurements over many decades. The report *International Global Network of Fiducial Stations: Scientific and Implementation Issues* (NRC, 1991) assessed the scientific importance of and implementation strategies for a global network of fiducial sites to support both geodetic and geophysical measurements. It recommended the establishment of a core network of roughly 30 fiducial stations, later called the Fiducial Laboratories for an International Natural Science Network (FLINN) to locate and integrate GPS receivers and instruments used by other scientific disciplines at sites already occupied by equipment devoted to geodetic techniques, such as Very Long Baseline Interferometry (VLBI) and Satellite Laser Ranging (SLR). In addition, the report advocated for the establishment of data centers to ensure a

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[2] Other related NRC reports include: *Geodesy in the Year 2000* (NRC, 1990); *International Global Network of Fiducial Stations: Scientific and Implementation Issues* (NRC, 1991); *Forum on NOAA's National Spatial Reference System* (NRC, 1994); *Airborne Geophysics and Precise Positioning: Scientific Issues and Future Directions* (NRC, 1995a); *The Global Positioning System: A Shared National Asset* (NRC, 1995b); *Satellite Gravity and the GeoSphere: Contributions to the Study of the Solid Earth and Its Fluid Envelope* (NRC, 1997a); *The Global Positioning System for the Geosciences: Summary and Proceedings of a Workshop on Improving the GPS Reference Station Infrastructure for Earth, Oceanic, and Atmospheric Science Applications* (NRC, 1997b); *Review of EarthScope Integrated Science* (NRC, 2001a); *Weaving a National Map: Review of the U.S. Geological Survey Concept of the National Map* (NRC, 2003); *Review of Goals and Plans for NASA's Space and Earth Sciences* (NRC, 2006); and *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond* (commonly called "the Decadal Survey;" NRC, 2007a).

smooth flow of data from the network operators to the user community and for the establishment of analysis centers to develop and test techniques that support part-per-billion, three-dimensional geodesy. Finally, the report *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond* (commonly called "the Decadal Survey;" [NRC, 2007a]) warned that the nation's geodetic infrastructure is now at a critical juncture:

> "The geodetic infrastructure needed to enhance or even to maintain the terrestrial reference frame is in danger of collapse (cf. Chapter 1). Improvements in both accuracy and economic efficiency are needed. Investing resources to assure the improvement and the continued operation of this geodetic infrastructure is a requirement of virtually all the [satellite] missions of every Panel in this study."

The terrestrial reference frame is realized through integration of the high-precision networks of the Global Positioning System (GPS), VLBI, and SLR. It provides the foundation for virtually all space-based and ground-based observations in Earth science and studies of global change, including remote monitoring of sea level, sea-surface topography, plate motions, crustal deformation, the geoid, and time-varying gravity from space. It is through this reference frame that all measurements can be interrelated for robust, long-term monitoring of global change. A precise reference frame is also essential for interplanetary navigation and diverse national strategic needs (NRC, 2007a, p. 223).

Other notable reports from which the committee has drawn include the "Williamstown Report" (Kaula, 1970), the "Erice Report" (Mueller and Zerbini, 1989), the "Coolfont Reports" (NASA, 1991a,b,c), the "Living on a Restless Planet" report of the Solid Earth Science Working Group of NASA (Solomon and the Solid Earth Science Working Group, 2002), the report on the InSAR Workshop (Zebker, 2005), and *Global Geodetic Observing System: Meeting the Requirements of a Global Society on a Changing Planet in 2020* (Plag and Pearlman, 2009).[3]

Building on these prior studies, this report assesses the scientific and societal benefits of precise geodetic observations and networks to the nation, discusses the associated requirements, explores opportunities for technological innovation, and suggests ways to improve national coordination and implementation of the geodetic infrastructure (Box S.1). It was not within the committee's charge, however, to consider budgets, to do a cost comparison, or to estimate the economic impacts of precision geodetic infrastructure, although such an evaluation would be useful.

Although the contributions of geodetic observations and infrastructure to modern science, commerce, and society are immense, they are mostly—with the notable exception of GNSS/GPS—hidden from the public eye. Because the responsibility for building and maintaining the geodetic infrastructure is distributed across a range of federal agencies, statements made by agency personnel concerning the importance of this infrastructure to the nation do not always resonate with policy makers and the public. It was in this context that the NRC was asked by several federal agencies—the National Aeronautics and Space Administration (NASA), the U.S. Naval Observatory (USNO), the National Geospatial-Intelligence Agency (NGA) of the Department of Defense (DoD), the National Science Foundation (NSF), the National Geodetic Survey (NGS) of the National Oceanic and Atmospheric Administration (NOAA), and the U.S. Geological Survey (USGS)—to provide an independent assessment of the benefits provided by the geodetic observations and networks, as well as a cohesive plan for the future development and support of the infrastructure as scientific and commercial users increasingly demand greater precision.

The committee addressed Tasks 1 through 5 of its charge (see Box S.1) by gathering information from the scientific literature, presentations, and discussions with representatives of the federal

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[3] The committee drew information and viewpoints from many relevant reports, but was not charged with either analyzing the previous recommendations or the reason for the lack of implementation. We do note some of the recommendations and warnings in these reports.

agencies that requested the study. The committee also received briefings from representatives of the Department of Transportation, as well as academic, nonprofit, and industry researchers. All presenters, with their affiliations and presentation titles, are listed in Appendix B. The committee also relied on relevant technical documents, pertinent NRC reports, and the collective expertise of the committee members. These considerations led the committee to develop recommendations focused on maintaining capability and mitigating the risk of infrastructure degradation, and supporting a long-term, sustainable national infrastructure capable of serving the full range of existing and future users.

ORGANIZATION OF THE REPORT

This report examines the national need for high-precision geodetic infrastructure. The remaining sections of Chapter 1 review the fundamental geodetic parameters, define what is meant by geodetic infrastructure for the purposes of this report, and outline the respective roles and responsibilities of federal agencies and offices with respect to the nation's precision geodetic infrastructure. Chapter 2 explores the potential of geodetic observations and networks to transform science and to promote broad societal applications. Chapter 3 describes the range of science and societal objectives that drive advances in geodetic observations and networks. Chapters 4 and 5 examine the requirements for maintaining a robust geodetic infrastructure, as well as the importance of the ITRF. Chapter 6 identifies key institutional and workforce issues and offers a plan for the long-term support of a national geodetic infrastructure capable of servicing the full range of existing and future users. Biographical sketches of the committee members (Appendix A), a list of presentations made to the committee (Appendix B), and a glossary of commonly used terms and acronyms (Appendixes C and D) appear at the end of the report.

FUNDAMENTAL GEODETIC PARAMETERS

The fundamental parameters of geodesy include the Earth's shape (land and sea surface topography, bathymetry, and ice sheet thickness), rotation and orientation in space, and gravity field. These parameters all change with time as a consequence of the dynamic nature of the Earth's system. Geophysical processes transform the Earth's surface, modify the distribution of mass within the Earth's interior and its oceans, and consequently alter its gravity field and rotation.

Geometric Shape of the Earth

The shape of the Earth's solid surface is described by land surface elevation (topography), the underwater surface of lakes and ocean floors (bathymetry), and ice surface elevation. These three surfaces are most often measured with respect to mean sea level, which approximately defines the location of zero on the measurement scale. The global *mean sea level* is the measure of the average height of the ocean's surface (the halfway point between the mean high tide and the mean low tide). In order to extend the definition of mean sea level to the land, we approximate it with a model of the Earth called the geoid (Figure 1.2). The *geoid* describes a surface to which the force of gravity is perpendicular everywhere (that is, a surface with uniform gravitational potential). If the oceans were undisturbed by currents, winds, and waves, then the mean sea level would correspond exactly with the surface of the geoid. In reality, external forces such as tides and weather cause the geoid and mean sea surface to differ; this difference is referred to as *sea surface height (or sea surface topography*).

Elevations—or more technically, *orthometric heights* (H)—are determined by calculating the height of the land surface above the geoid (Figure 1.2). The precise determination of elevation is

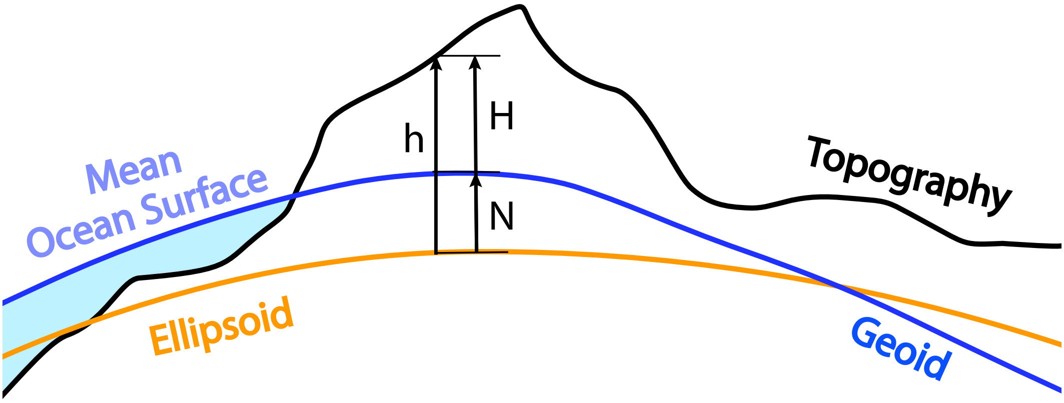

FIGURE 1.2 Schematic showing the approximate relationship between the geoid, based on the Earth's gravity field (and coinciding with the mean sea level), and the surface of the Earth (topography). Surveys using spirit leveling measure height differences along the geoid. Water flows downhill as defined by the orthometric heights (H). On the other hand, geometric heights (h) are reckoned relative to a conventional ellipsoid and are calculated from coordinates relative to the center of the Earth. In order to use such heights for flood modeling, an independent knowledge of the orthometric height relative to the ellipsoid (N) is required, known as the geoid height. This calls for densely sampled maps of the gravity field, which can be greatly improved nowadays by airborne surveys using GPS/GNSS navigation. Source: Committee on the National Requirements for Precision Geodetic Infrastructure.

important for a wide range of applications, including floodplain mapping and storm surge modeling. Vertical positions determined from GNSS/GPS are not connected to the geoid but represent an absolute height—called the *geometric height (or ellipsoid height)* (h)—calculated from coordinates whose origin is at the center of the Earth. The vertical distance from the ellipsoid and the geoid at any location on Earth is called the *geoid height* (N). Independent knowledge of the geoid allows geodesists to relate geometric to orthometric heights and, for example, to infer land surface elevations from GNSS/GPS measurements.

Time and the Earth's Rotation

The Earth spins and wobbles in complex ways, causing the positions of the poles to shift by millimeters over the course of a day and by meters over the course of a year. Day-to-day variations in the length of day (which measures the Earth's rate of spin) are typically on the order of fractions of milliseconds per day. The length of day also gradually lengthens as energy is dissipated—primarily through tidal friction—requiring the occasional "leap second" that is applied by international convention.[4]

One of the primary roles of the global geodetic infrastructure is to determine the length of day and Earth orientation parameters and how they change with time relative to the Earth's interior, as well as how they change relative to distant, "fixed" objects such as quasars. This requires the ability to synchronize distant clocks accurately, an operation commonly referred to as "time transfer." Time synchronization is less stringent for such everyday functions such as bank transfers, transportation, television broadcasting, and power grid regulation (i.e., on the order of milliseconds or less). Even higher accuracy is needed for modern high-bandwidth digital networks. GNSS/GPS signals are the

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[4] The changes in Earth's spin rate and the wobbles of its rotation axis also affect the evolution of a terrestrial reference frame over time. Motions of geodetic targets, either satellites or quasars, are modeled in a non-rotating system. To relate their instantaneous coordinates to Earth-fixed systems requires knowledge of the Earth orientation parameter with the same accuracy as the terrestrial coordinates.

most popular and economical way to achieve clock synchronization for most of these commercial applications. Scientific applications, on the other hand, have yet more demanding time synchronization requirements, at the nanosecond level (10^{-9} seconds) or better. Thus, the high-accuracy methods at the heart of geodetic techniques enable precise measurements of time and frequency, as well as tests of fundamental physics, including the Theory of General Relativity. "Precise time-transfer" is typically only needed to synchronize clocks with comparable precisions (for example, atomic clocks). Because the international definitions of time (International Atomic Time and Coordinated Universal Time) are based on careful combinations of the records from approximately 300 atomic clocks, the precision of the time-transfer method is just as important as building the clocks themselves (Arias, 2005). The United States has demonstrated its long-standing commitment to the definition of International Atomic Time by contributing more than half of the clocks used to define the international timescale.

Gravity

Gravity, as measured on the Earth's surface, depends on the distribution of mass within the entire Earth system. Therefore, spatial and temporal changes in mass (in density, volume, or both) in the Earth's solid and fluid interior, atmosphere, oceans, hydrosphere, and cryosphere—such as seasonal snowpack and groundwater changes or post-glacial rebound—can be detected as corresponding variations in the Earth's gravity. Gravity measurements also can distinguish the underlying mechanisms behind mass redistribution, such as thermal expansion of the ocean or the addition of water from the melting of continental ice sheets, which are both contributing to global sea level rise. Because these gravitational variations are one thousand to one billion times smaller than the mean value of gravity of the Earth (approximately 9.81 meters per second squared), precise geodetic observations are needed across regional and global scales and over long periods of time. The precision of gravity measurements has improved by roughly three orders of magnitude over the past 50 years, and is currently at one part per billion (Plag and Pearlman, 2009).[5]

Gravity measurements obtained from the GRACE (Gravity Recovery and Climate Experiment) satellite mission (discussed in Chapter 3), launched in 2002, have led to improvements in the accuracy of the geoid to the centimeter level (Tapley et al., 2004a,b), and consequently to improvements in the reliability of the National Spatial Reference System (NSRS). The NSRS, managed by NOAA's NGS, is a consistent national coordinate system that specifies latitude, longitude, height, scale, gravity, and orientation throughout the nation, and tracks how these values change over time (NRC, 1994, 2003). Variations in the gravity field over time can be large enough to affect the NSRS.

Because variations in the gravity field perturb the orbits of satellites, an accurate model of the Earth's gravity field is needed to correctly predict their positions. Similarly, an accurate gravity model improves the accuracy of other geodetic techniques, such as satellite altimetry and synthetic aperture radar interferometry, and aids the development of digital terrain models.

THE GEODETIC INFRASTRUCTURE

Geodetic observing systems provide a significant benefit to society in an astonishing array of commercial and scientific areas with a wide range of precision requirements. Underlying these observing networks is the precise geodetic infrastructure, made up of a variety of components. In this report, the committee distinguishes between *geodetic observing systems* and *geodetic infrastructure*.

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[5] Monthly global maps of the Earth's gravity field derived from the GRACE mission verify the earlier NRC assessment (NRC, 1997a) that "the time-varying effects [of gravity] are three to four orders of magnitude smaller than the static field variations, so dense temporal and spatial coverage and highly accurate measurements are necessary" (see Reigber et al., 2005).

Although these overlap, the two are distinguished by their primary purpose. When the committee refers to *geodetic observing systems* (or in some cases *geodetic observing networks*), it refers to systems that are designed to address specific goals (such as measuring sea level changes) and may be used for a finite period of time. ***Geodetic infrastructure*, on the other hand, supports all observing systems and applications over time; its main function is to provide necessary information for the *International Terrestrial Reference Frame* (ITRF) that underpins many Earth observation missions and location-based applications.** The strength of the infrastructure lies in its longevity, continuity, stability, robustness, accuracy, speed of accessibility, and its capability for supporting innovation through the development of new observing systems that exploit the accuracy of the infrastructure. Geodetic observing systems therefore rely on the existence of the geodetic infrastructure to achieve their goals.

In the broadest sense, the geodetic infrastructure includes the following:

- Geodetic bench marks in the ground that define specific locations;
- Ground-based geodetic system hardware that may range in size, cost, and complexity from GNSS/GPS receivers to large radio telescopes or satellite laser-ranging systems;
- Ground and airborne systems for the measurement of gravity;
- Tide gauges;
- A host of satellite systems for radar, LiDAR (Light Detection and Ranging), and gravity measurements;
- The data analysis that turns geodetic observations into geographic and other information, including the ITRF;
- The systems that define procedures for data analysis and combination; and
- Computer systems for archival of raw data and data products.

This report focuses on those components of the geodetic infrastructure that contribute globally, in particular the four geodetic hardware systems and associated services that form the backbone of the ITRF.

Very Long Baseline Interferometry (VLBI)

Based on a technique developed for astronomy, VLBI uses fairly large, ground-based, parabolic-dish radio telescopes to observe quasars (the most distant objects in the cosmos), thus providing a connection to the "outside universe." A small network of VLBI sites provides critical information on the direction of the Earth's spin axis against this background constellation of quasars and allows the Earth's rotation to be connected to this stable background.

Satellite Laser Ranging (SLR) and Lunar Laser Ranging (LLR)

In this technique, a laser signal is transmitted from a ground-based station, reflects off specially designed mirrors (retro-reflectors) placed on artificial satellites (SLR) or on the moon (LLR), and is received back at the station. Satellites and the moon orbit the Earth due to the Earth's gravitational pull. This technique therefore provides a unique connection between the Earth's surface and its gravity field, which reflects the distribution of mass deep within the planet.

Global Navigational Satellite Systems (GNSS)

This is a generic term for satellite navigation systems that provide autonomous spatial positioning with global coverage. The U.S. NAVSTAR Global Positioning System (GPS) falls into this category; other countries also have or are developing GNSS systems. Coded signals transmitted from multiple satellites and received by multiple GNSS receivers allow time delay, and indirectly distance, measurements between the satellites and GNSS receivers. Although GNSS/GPS is designed to be accurate to the meter level, geodesists have determined how to use these signals to achieve accuracies 1,000 times better. The strength of these systems lies in the low cost of the ground-based systems (the systems do not include satellites) compared to VLBI or SLR/LLR. GNSS, therefore, provides a geographic coverage unequaled by these other systems because they can be inexpensively deployed and have a wide range of applications.

Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS)

DORIS is a tracking system developed and operated by France. In some respects, it is an inversion of GNSS/GPS because the transmitters are on the ground and the receivers are on satellites. Many of the same principles that apply to GNSS/GPS also apply to DORIS. DORIS was designed for precise orbit determination required by ocean altimeter satellites and therefore helps connect sea-level measurements to the solid Earth.

These systems together provide some of the most important measurements of the Earth's short-term (daily and shorter) and long-term (years and longer) motions, including deformation (Figure 1.3). To obtain these measurements, the information acquired by these infrastructure systems travels a long path. The data from each system (blue boxes in Figure S.2) are analyzed (red boxes) to provide intermediate data products, which are then combined to yield the information (green) that can then be easily incorporated into other observing systems by users (cyan). Thus, at the lowest levels, these systems must be coordinated to ensure that there is complete consistency. In fact, the global geodetic community has worked for decades to provide common standards for analysis and data formats for the precise *global* geodetic infrastructure, of which the United States' geodetic infrastructure is a leading component.

Professional geodesists are as important to the field of geodesy as the infrastructure itself. The measurements gathered by the instruments have no value without being analyzed and incorporated into models of the physical world. Formal training in geodesy includes study across a broad range of topics that provide the analytical tools and the knowledge of the observational systems needed to carry out research in this field. A "geodesist," therefore, might be defined as someone with formal training in the following areas, which can be thought of as the building blocks of a geodetic education:

- *Positioning and reference systems*. The methods for describing the location of positions on the surface of a changing planet at ever-increasing levels of precision.
- *Gravity field theory.* Mathematical approach for describing the gravitational field of a planet, including, in the case of the Earth, such geometric constructs as mean sea level.
- *Dynamics of the Earth's rotation.* Observations on the small variations in the rotation of the Earth, which provide unique probes into the structure of the planet and the mass variations within the planet and on its surface.
- *Crustal deformation due to mass load changes.* Investigations on how the Earth's crust deforms due to an increase (such as the extra weight of water at the land's edge at high tide) or a decrease (such as loss of ice in a polar ice sheet) in the mass load. These investigations provide information about the planet's crust and mantle composition, as well as the nature of the forcing of that deformation from loading due to ocean tides, atmospheric pressure, ice and water variations, and other changes.
- *Propagation of radio waves through the atmosphere.* Study of how the atmosphere refracts radiometric signals. Signal delays provide a measure of air density, moisture content, and charged particles.

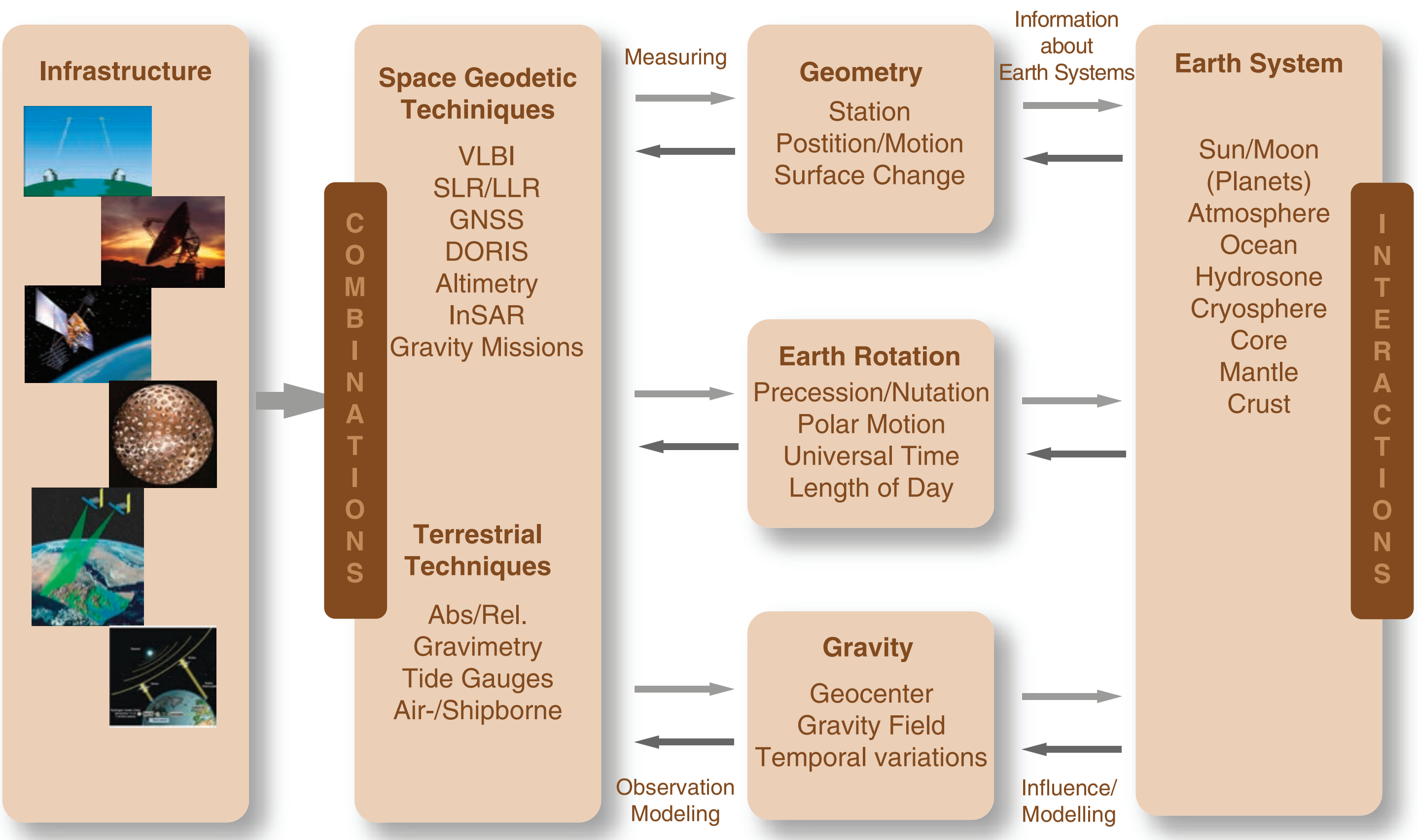

FIGURE 1.3 Precision geodetic techniques, supported by the geodetic infrastructure, determine the time-dependent geometry, rotation, and gravity field of the Earth. SOURCE: Adapted from Plag and Pearlman (2009) with permission from Springer and Rummel (2010) with permission from Elsevier.

- *Satellite orbit determination.* The science of determining an orbiting satellite's position as a function of time, an essential component of accurate geodetic measurements. This involves complex mathematical modeling of the physics of spacecraft motion and ingesting the available tracking data into that model through various estimation techniques.
- *Techniques for estimating model parameters from observational data and error analysis of those estimates.* The process of estimating unknown or poorly known parameters for a mathematical model. To be useful, an assessment of the accuracy of these estimates is also essential.

A geodesist combines these areas of knowledge to achieve the goals of his or her work. This work may be purely theoretical, it may use one or more of the geodetic observation techniques discussed in this report, or it may involve the development of new geodetic techniques and observing systems. Although some of the above topics may be part of a course of study in other disciplines, the combination of these topics is unique to the science of geodesy.

FEDERAL SUPPORT FOR THE GEODETIC INFRASTRUCTURE

Within the United States, support for precision geodetic infrastructure is provided by a number of agencies and offices, including, FAA, NASA, NGA, NOAA, NSF, PNT, USGS, and USNO. Other agencies, such as the U.S. Department of Agriculture (USDA) and the Environmental Protection Agency (EPA), assist with coordination and are users of precision geodetic information. The respective roles and responsibilities of these agencies are summarized in Table 1.1.

Federal Aviation Authority (FAA)

The FAA is focused on public safety and reliability, but uses relative positioning, rather than precision and absolute positioning. FAA has developed a separate infrastructure to meet its specific demands.

National Aeronautics and Space Administration (NASA)

Starting in the 1960s, NASA has been a leader in researching and developing geodetic techniques and coordinating the deployment of the associated global infrastructure (see Kaula, 1970). Initially, the primary technologies developed by NASA included VLBI, SLR, and LLR. These technologies came to fruition in the 1980s under the Crustal Dynamics Project, allowing geodesists to determine coordinates of sparse global networks with sufficient accuracy to measure directly the rates of motion (velocities) of these points at the centimeters per year level—and much better over time—and thus map truly "instantaneous" tectonic motions. In the 1990s, civilian networks of permanent GPS stations were developed and deployed, first in southern California and Japan, and later globally, thereby permitting the production of detailed, time-dependent deformation maps in seismic and volcanic areas. Further advances led to precise satellite orbits derived from onboard GPS receivers, and more recently ultra-precise (to an accuracy of 10 centimeters) navigation of manned and unmanned aircraft anywhere in the world.

Almost all space missions rely directly or indirectly on the precise, global geodetic infrastructure. This includes both U.S. and foreign missions. Of special note are:

- LAGEOS and similar passive geodetic satellites (for example, Etalon and Starlette) that led to major advances in geoid determination
- Radar imaging missions (for example, SeaSat , Geosat, SRTM, and Envisat)
- Radar and LiDAR altimetry missions (for example, TOPEX-Poseidon, Jason, and ICESat)

TABLE 1.1 Main Government Stakeholders (Users of and Contributors to) the Precise, Global Geodetic Infrastructure

Organization	Contributor	User	Notes
NASA	Yes	Yes	Provides primary support for critical U.S. geodetic infrastructure components of global ground-based networks; supports fundamental geodetic research; supports development of the Global Geodetic Observing System; supports geodetic infrastructure critical to many satellite missions.
DoD	Yes	Yes	Operates the Global Positioning System (GPS); supports heavy military usage of GNSS/GPS; supports geodetic infrastructure used to improve GNSS/GPS; USNO provides many GNSS/GPS-based products that rely on geodetic infrastructure.
NGA	Yes	Yes	Relies on geodetic infrastructure to provide geospatial intelligence; supports, and maintains WGS-84 (DoD Terrestrial Reference System)
NGS	Yes	Yes	Relies on geodetic infrastructure to provide CORS data products (used by surveyors) and for NSRS; performs analysis of global data for reference frames and orbits; proposed GRAV-D for redefinition of U.S. vertical reference datum.
NOAA (non-NGS)	No	Yes	Uses geodetic infrastructure to support ground-based water-vapor measurements for weather forecasts, climate observing system (COSMIC), tsunami warning, and sea-level change.
NSF	Yes	Yes	Relies on geodetic infrastructure for studies of tectonics, volcanoes, earthquakes, glaciology, and climate; supports infrastructure for U.S. observing systems that rely on geodetic infrastructure (for example, EarthScope/PBO).
PNT	No	Yes	Advises and coordinates federal departments and agencies on matters concerning GNSS/GPS.
USGS	No	Yes	Relies on geodetic infrastructure for analysis of USGS geodetic networks used to asses risks from earthquakes and volcanoes.
DoT	No	Yes	Uses GNSS/GPS, but uses do not require the highest precision; FAA operates independent networks for air traffic operations and WAAS.
State and local governments	No	Yes	Surveying for roads, highways, and property; primary government interface with civilian surveyors and engineers.

- Gravity measurement missions (for example, CHAMP and GRACE)
- Atmospheric and ionospheric sounding (GPSMet, Champ, SAC-C, and COSMIC)

In addition to the infrastructure, NASA historically has supported fundamental research and development programs in space geodesy and continues to do so (with increased emphasis on real-time dynamic applications and high spatial and temporal resolution of climatic and tectonic forcings). It is, therefore, not surprising that there is a NASA influence in the treatment of many global scientific problems, including sea-level change, ice budget, ocean circulation, climate change, and geohazards.

National Geospatial-Intelligence Agency (NGA)

The mission of the NGA Office of GEOINT Sciences is to provide accurate and timely geodetic, geophysical, and geospatial analysis and intelligence information to support the DoD's national security and intelligence objectives. The NGA supports satellite geodesy by maintaining its permanent GPS tracking network and implementing improvements to GPS orbit determination. The NGA also works to maintain and improve the World Geodetic System 1984 (WGS 84), the reference frame currently used by GPS and the Department of Defense. Further, NGA is responsible for collecting, processing, and evaluating geodetic data, which are used to compute the WGS 84 Earth Gravitational Model, geomagnetic models, and global digital terrain models.

National Oceanic and Atmospheric Administration (NOAA)

NOAA, through the National Geodetic Survey (NGS), has the federal mandate for defining, maintaining, and providing access to the National Spatial Reference System (NSRS). The NSRS allows consistent positioning to meet a wide range of needs, from delineating property lines and exclusive economic zones to determining the heights of levees and tide gauges relative to sea level. Historically, NGS installed thousands of survey monuments across the nation in support of the NSRS. By establishing a network of Continuously Operating Reference Stations (CORS) using GPS and by making the observational data available, NGS now allows users to connect directly to the NSRS without the need to place receivers at NGS survey monuments. Each CORS site provides GPS carrier phase and code range measurements to support three-dimensional positioning activities throughout the United States and its territories, with accuracies that approach a few centimeters, measured in the NSRS, both horizontally and vertically. The CORS system is operated in partnership with many local, state, and federal agencies, and contains CORS stations that are located at sites of varying positional stability and with various models of receivers, antennas, and documentation.

In cooperation with the USGS, NOAA also has responsibilities for supporting the geodetic infrastructure to provide ocean bathymetry, coastline and sea surface topography, which are critical for understanding tsunamis and predicting where they might come ashore, as well as for determining local or regional changes in sea level. NOAA further cooperates with NASA and USNO in the National Earth Orientation Service, or NEOS. NOAA's National Geodetic Survey chairs the Federal Geodetic Control Subcommittee (FGCS) of the Federal Geographic Data Committee (FGDC), with membership drawn from all federal agencies involved in surveying, mapping and geospatial data, to promote a common standard of content, format and accuracy for geodetic data for the nation.

National Science Foundation (NSF)

The NSF supports a large number of scientific research projects that depend on the geodetic infrastructure. In addition, the NSF supports national geodetic infrastructure through financial support for the UNAVCO Facility (formerly known as the University NAVSTAR Consortium) and the

EarthScope program, which facilitate testing, adoption, and implementation of geodetic technologies to support fundamental geodynamic research, such as the study of earthquakes and volcanic eruptions. The Plate Boundary Observatory (PBO)—a component of EarthScope—provides geodetic imaging of plate boundary deformation.

National Space-Based Positioning, Navigation, and Timing (PNT) Executive Committee and Coordination Office

The National Executive Committee for Space-Based Positioning, Navigation, and Timing (PNT) coordinates policy activities relating to the Global Positioning System (GPS) and Global Navigation Satellite Systems (GNSS). It is chaired jointly by the Deputy Secretaries of Defense and Transportation. The Space-Based PNT National Coordination Office staffs the operational activities of the National Executive Committee. A formal Federal Advisory Board provides external advice and recommendations on PNT issues to the National Executive Committee.

U.S. Geological Survey (USGS)

Although data from some GPS stations operated by USGS are processed by the International GNSS Service, they are not used to to maintain the International Terrestrial Reference Frame. USGS depends on geodetic infrastructure to cary out its earthquake and volcano monitoring mission, and that infrastructure is crucial to development and production of data products, such as hazard maps and real-time ShakeMaps.

U.S. Naval Observatory (USNO)

The USNO is responsible for establishing, maintaining, and coordinating the astronomical reference frames for celestial navigation and orientation of space systems. Specifically, the USNO is the sole provider of the Earth Orientation Parameters (EOP) to the Department of Defense. USNO also serves as the official source of time for the Department of Defense and a standard of time for the entire United States.

International Services

Many international services have been established in response to the need for international cooperation to support geodetic activities. The most important of these services are the International Earth Rotation and Reference System Service (IERS) (Vondrák and Richter, 2004); the International GNSS Service (formerly the International GPS Service, or IGS) (Dow et al., 2005); the International VLBI Service (IVS) (Schlüter et al., 2002); the International Laser Ranging Service (ILRS) (Pearlman et al., 2002); and the International DORIS Service (IDS) (Tavernier et al., 2006). These services are described in more detail in Chapter 4. In general, the Central Bureau for each service is supported by the host country with volunteer contributions by the international scientific community. For example, the Central Bureaus for the IGS, IVS, and ILRS are all hosted in the United States and are supported by NASA.

2

Geodesy for the Benefit of Society

The modern global geodetic infrastructure was developed over the past several decades primarily to support activities in the scientific and military communities. Nevertheless, the physical, computational, and organizational infrastructure developed for these communities now support a wide range of applications. Like roads and highways that facilitate interstate commerce, the geodetic infrastructure provides significant benefits to society by enabling an astonishing array of activities and innovations, including autonomous navigation, precision agriculture, civil surveying, early warning systems for hazards, and improved floodplain mapping. This chapter describes current capabilities made possible by the precise global geodetic infrastructure, highlights areas that could benefit from improvements in the geodetic infrastructure, and explores potential future applications.

CURRENT BENEFITS OF THE GEODETIC INFRASTRUCTURE

Accurate Topography Maps

Topography (land surface elevation, also called terrain) provides an important, basic component for many applications. Scientists use topographic maps to study plants and animals, geology, hazards, and erosion. The National Research Council (NRC) (2007b, p. 2) found that "topographic data are the most important factor in determining water surface elevations, base flood elevation, and the extent of flooding and, thus the accuracy of flood maps in riverine areas." Accurate topographic maps also are important for civilian applications from aircraft navigation to hiking and backpacking. The base layer in Google Earth© is constantly being updated using the latest topographic data. Topography is also important for such commercial applications as determining the optimal placement of cell-phone towers, planning pipelines, and routing trucks for fuel efficiency. The most accurate global map of the Earth's topography (to an accuracy of 5–10 vertical meters) was obtained during the 11-day Shuttle Radar Topography Mission (SRTM) in 2000 (Farr et al., 2007). The next generation of U.S. topography surveys is being performed at a much higher vertical accuracy—an accuracy of 10 centimeters or better. These high-accuracy surveys are performed by aircraft radar and LiDAR (Light Detection and Ranging) and make extensive use of the geodetic infrastructure for determining flight paths to centimeter accuracy after the data are collected.

Improved Floodplain and Inundation Maps

Floodplain maps are used to predict how water will flow on the Earth's surface and are crucial to assessing the risk of floods. The creation of floodplain maps is an important part of the National Flood Insurance Program because these maps are used for setting flood insurance rates, regulating floodplain development, and communicating the one percent annual chance of flood hazard. The Federal Emergency Management Agency (FEMA) is undertaking an ambitious five-year program to update and make digital the floodplain maps of the nation (NRC, 2007b). These maps are derived from a combination of topographic data (elevations to an accuracy of 10 centimeters or better) and map of the geoid (refer to Figure 1.2), because water flows downhill relative to the undulating geoid surface. The North American Vertical Datum of 1988 (NAVD 88) is the official reference surface against which elevation measurements are made in the United States. NAVD 88, however, has an average bias of 1 meter and erroneous tilt amounting to an additional 1 meter error across the coterminous United States; it also has a 1–2 meter bias in Alaska (Childers et al., 2009a). Improving the accuracy of floodplain maps, therefore, will require improving the vertical datum, which in turn will require the use of either denser and more accurate geodetic leveling observations or Global Positioning Systems (GPS) measurements and a high-accuracy geoid model (NRC, 2007b). The National Geodetic Survey (NGS) has embarked on the GRAV-D Project (Gravity for the Redefinition of the American Vertical Datum), an airborne gravity mission to measure gravity and its changes more accurately than was previously achievable (NOAA, 2010; see Box 5.2). The goal of GRAV-D, therefore, is to model and monitor the Earth's geoid, which serves as the reference surface for zero elevation. The new gravity-based vertical datum resulting from this project will be accurate at the 2 centimeter level for much of the country. The benefit of GRAV-D to society has been estimated at $4.8 billion over 15 years (Leveson, 2009).

Uses of Real-Time Geodetic Positions

Accurate real-time locations are used in a wide range of commercial applications and services. Accurate positions of Global Navigation Satellite System (GNSS)/GPS satellites in their orbits and a terrestrial reference frame are used to determine the location of an object on the surface of the Earth accurately. The NGS Continuously Operating Reference Station (CORS) Network, which enables precise real-time positioning for applications, including precision agriculture, surveying, and even GPS-guided snowplows, makes extensive use of the global geodetic infrastructure. The CORS Network, in turn, is a fundamental component of the National Spatial Reference System (NSRS),[1] which provides a highly accurate and consistent geographic reference framework throughout the United States, allowing various layers of data to be spatially registered and integrated within geographic and land information systems (GIS/LIS). The NSRS has been estimated to provide benefits equivalent to $2.4 billion annually (Leveson, 2009). The NSRS, in turn, is the backbone of the National Spatial Data Infrastructure (NSDI), which was recognized in a 2004 report by the Federal Geographic Data Committee as the "primary mechanism for assuring (national) access to reliable geospatial data" (NSDI Future Directions Planning Team, 2004).

Real-time positioning data are often used by commercial augmentation services that provide corrections to standard GPS positioning to a global set of customers requiring sub-meter and deci-

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[1] The NSRS, defined and managed by the NGS, is a consistent national coordinate system that specifies latitude, longitude, height, scale, gravity, and orientation throughout the United States, as well as how these values change with time.

meter-level real-time positioning. These customers are involved, for example, in the offshore oil industry, precision agriculture, and certain marine applications, which require high reliability and global availability. Operators of earth-orbiting imaging satellites require rapid and precise geolocation of their images in order to provide rapid service to their customers. The global nature of many of these applications requires the products to be accurate in a well-defined and stable terrestrial reference frame.

Global Positioning System Monitoring and Improvement

The global geodetic infrastructure also contributes to improvements in the Global Positioning System (GPS). For example, geodetic research has led directly to the addition of a third GPS frequency and to the laser retroreflectors that may be added to future GPS satellites. In addition, the NASA Global Differential GPS (GDGPS) System[2] uses the global GPS network to perform integrity monitoring and situational assessment of GPS in real time for the U.S. Department of Defense (NRC, 1995b). The GDGPS is also the basis for the real-time orbit improvement for the Advanced Control Segment, an Air Force-sponsored project that will improve the accuracy of GPS.

Accurate Satellite Orbits

Satellites now provide a range of crucial services, including weather forecasts, communications, and land-use monitoring. By simply including a GNSS/GPS receiver on any satellite, it is possible to determine where that satellite is in its orbit. When the highest accuracy is required, it is necessary to supplement GNSS/GPS data with information from the global geodetic infrastructure, including the International GNSS Service network and the International Terrestrial Reference Frame (ITRF). In addition, models of the Earth's gravity field based on geodetic observations, as well as geodetic observations on the location of the Earth's rotation axis and rotation rate, are needed to determine the gravitational forces on the satellite (see Chapter 3). The existing geodetic infrastructure makes it possible to accurately position satellites for a wide range of applications; this capability is crucial to many of the proposed "Decadal Survey" missions, especially radar and laser altimetry missions (for example, SWOT, LIST, and ICESat-II), radar imaging missions (for example, DESDynI), and gravimetry missions (for example, GRACE-II) (NRC, 2007a).

Space Exploration

In addition to applications focused on the Earth, geodesy has played and will continue to play an important role in the exploration of the solar system and regions beyond. Systems that prove successful on the Earth can be applied to other planetary bodies. For example, the GRAIL (Gravity Recovery and Interior Laboratory) project uses an approach for determining the moon's gravity field that was pioneered by the GRACE (Gravity Recovery and Climate Change) project focused on the Earth.

Until we actually dig into the Earth or another planet, we must rely on information derived from surface observations, such as seismic and geodetic measurements, to learn about the interior structure. Zumberge et al. (2009) provide the example of Mars, which has had the precession of its rotation axis measured, and its gravity field and terrain mapped, using geodetic techniques. These observations have led to estimates of the size, mass, and physical state of the Martian core and to inferences about the seasonal variability of mass in the Martian polar icecaps.

In addition, the geodetic infrastructure is needed to track the location of spacecraft from Earth. As spacecraft get farther and farther away, the demand on the angular resolution of the tracking

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[2] NASA Global Differential GPS (GDGPS) System Website: *http://www.gdgps.net*

becomes increasingly strict. The Voyager I and Voyager II spacecraft, launched in 1977, are now 17 and 14 billion miles from Earth, respectively. These spacecraft are so far away and so faint that to track them requires geodetic techniques that were developed to determine the position of quasars at the edge of the universe. These techniques require accurate geodetic information on the location of the tracking sites on Earth, as well as details of the Earth's rotation axis (variations of the direction of the Earth's spin axis and rate of rotation).

TRANSITION FROM INNOVATIVE RESEARCH TO FUTURE APPLICATIONS

The past several decades have seen an increase in the accuracy of geodetic positioning of approximately one order of magnitude per decade, from approximately 1–10 meters accuracy in the mid 1970s to approximately 1 millimeter currently. This tremendous advance is due not only to technological improvements and cost reductions but also to the coordination of the scientific community through global geodetic services, including the International GNSS Service, the International VLBI Service, the International Laser Ranging Service, and the International DORIS Service; to geodetic research that led to significant improvements in geodetic data analysis and accuracy; and to coordination between the scientific and civilian communities and government.

Recent advances have been spectacular; it is unclear whether the past rate of improvement can be sustained, but the evidence indicates that the future will bring significant advances in geodesy in the areas of temporal resolution, spatial coverage and resolution, and latency.[3] The current trend is toward what might be called "geodetic imaging," a description of the Earth's continuous deformation at a high temporal and spatial resolution in near real time (see below, "Future Scientific and Technological Breakthroughs"). Many emerging applications take advantage of this trend. For example, real-time warning and response systems for hazards, including earthquakes, volcanic eruptions, tsunamis, and landslides, require both low data latency (delay of less than one second) and high temporal resolution (sampling rate of one hertz or higher). In addition, increased spatial and temporal coverage from geodetic techniques can improve weather forecasting, water-resource monitoring, studies of earthquake-related deformation, and research on how glaciers respond to climate change. Commercial applications including autonomous navigation and precision agriculture require wide spatial coverage and high accuracy in real-time. The development of near-real-time applications with high spatial and temporal resolution also places a new burden on the geodetic infrastructure, requiring it to be increasingly robust.

The geodetic infrastructure—and the research, analysis, and international coordination that support this infrastructure—will need to evolve to meet these challenges. The infrastructure required to make future applications a reality does not yet exist, and in most cases the research in these areas is not yet complete. A detailed discussion of the benefits to society of the global geodetic infrastructure can be found in Sahagian et al. (2009). Here, we review several developing and future applications.

Early Warning for Natural Hazards

For many centuries, humans have strived to provide warning of nature's most violent and hazardous events. Some of these events—earthquakes, volcanic eruptions, and tsunamis—are caused by deformation of the Earth's crust. Although these events cannot be predicted beforehand, rapid detection of them can lead to early warning and response. Even a few seconds of warning can allow people to take action that can save lives and reduce the cost of an event (see Box 2.1).

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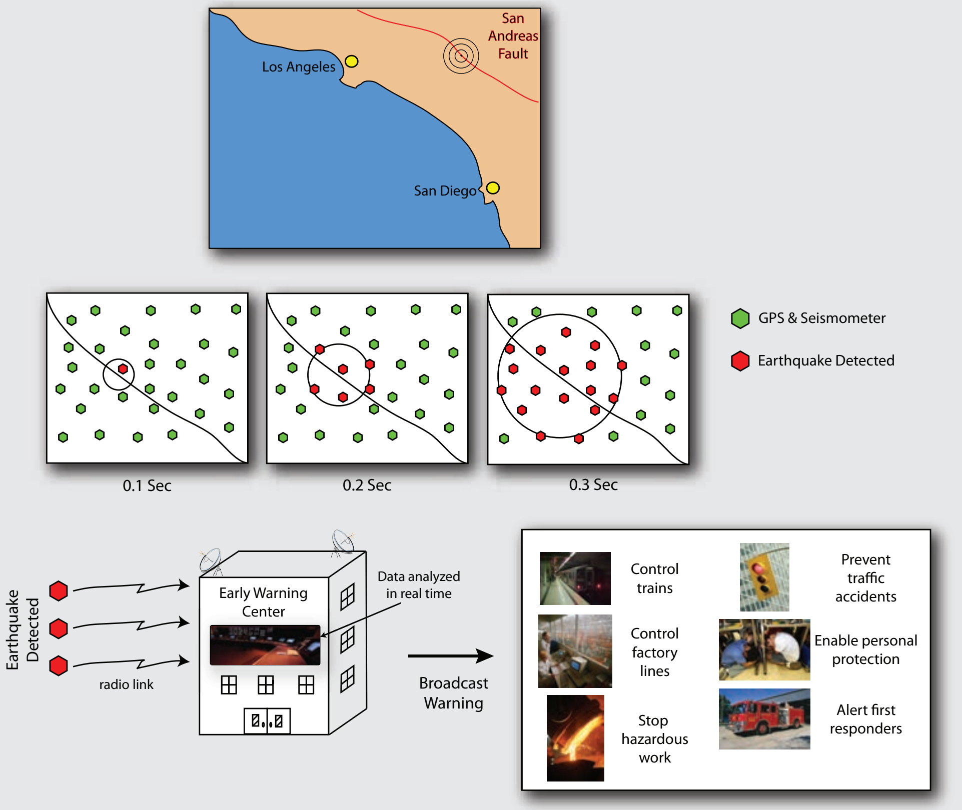
[3] Latency refers to the time delay between the acquisition of data and the distribution of products derived from that data. "Low latency" means a short delay.

BOX 2.1



Sketch illustrating the concept of earthquake early warning. Energy from an earthquake occurring, for example, on the San Andreas Fault (top frame) propagates outward. As this energy propagates, it would cause ground motion at more and more sites of the combined GNSS/GPS-seismological network (center row). If the earthquake is large, the seismometers close to the rupture may “clip” (max out), but data from the GNSS/GPS sites can be used rapidly to determine earthquake location, size, and potential for damage to urban structures. Early warning for tsunamis and landslides would work on a similar basis.

There are currently many nascent efforts to study how geodetic data can improve our capability for early warning. A critical question seismologists face when they sense seismic activity is: “Is this a small earthquake, or the first indications of a large one?” Because of the physics of seismic wave generation and propagation, that question is not easily answered with seismic data alone. Real-time geodetic data could help answer that question. In addition, even a sparse geodetic network delivering data in real-time could help scientists determine whether a large earthquake will generate landslides or a tsunami (see Blewitt et al., 2006), such as the large tsunami caused by the December 24, 2004, Sumatra earthquake (Plag and Pearlman, 2009).

For geodesy to contribute to early warning systems for such hazards, geodetic instrumentation (ground- or space-based, or both) is needed in the areas that are most likely to be affected. Further infrastructure is required to collect, analyze, and interpret the data and to communicate it to the proper governmental authorities. All of this activity has to take place in as little time as one second for an earthquake. Due to the low tolerance for delay in such applications, the highest real-time accuracy is needed, which requires making full use of the global geodetic infrastructure. In addition, GNSS/GPS satellite orbits and Earth rotation variations would need to be extrapolated into the near future for accurate data analysis. Early warning systems for hazards also would rely on advance coordination and up-to-date station information. Demonstration of such approaches will have to be carried out under strict guidelines before they are integrated into societal response to these hazards.

Autonomous Navigation

In the United States, more than 33,000 people were killed in highway accidents in 2009 (National Highway Traffic Safety Administration, 2009). According to Urmson and Whittaker (2008), "[t]he prevailing belief in the automotive industry is that the benefit of passive safety systems such as seat belts and air bags has reached a plateau. To improve safety, vehicles must avoid crashes rather than attempt to survive them."

The advent of precise positioning in real time has allowed the widespread development of autonomous vehicle navigation systems. The capability of these systems depends on the accuracy and robustness of the positioning systems; the accuracy of the geographic information system data against which the vehicle is referencing its location to find its position relative to other objects; ancillary sensors that allow fine-tuning of position and velocity information and the detection of obstacles; and the software that assimilates incoming sensor data and controls the vehicle.

GPS already has been successfully applied in autonomous vehicle navigation. One of the earliest applications of vehicle control using GPS dates to the early 1990s, when GPS systems were first used to perform automatic aircraft landings. There have been many successful applications of these methods, which often supplement the standard GPS satellite signals with an additional GPS signal from near the runway on which the aircraft will land (see LeMaster, 2003). Commercial GPS aircraft landing systems are now being certified by the Federal Aviation Administration (see *Military and Aerospace Electronics*, December 17, 2008). On land, the Defense Advanced Research Projects Agency's (DARPA's) Urban Challenge demonstrated that autonomous navigation in complex urban settings is possible (DARPA, 2007).

Improved accuracy of the GPS and other GNNS systems will benefit autonomous vehicle applications by improving real-time positioning capabilities and leading to improved GIS databases that allow vehicles to register their position against geographical features. Although the demands on the infrastructure are great and legal impediments such as liability will need to be addressed, real-time vehicular positioning with centimeter accuracy is a future possibility. The deployment of multiple GNSS systems will provide more robust positioning in areas of restricted sky visibility, such as urban centers.

Active Remote Sensing

Information about the surface of the Earth acquired from airborne or spaceborne platforms is a crucial aid to agriculture, forestry, resource management, and science. Remote electromagnetic sensing of land cover and land use, surface deformation due to earthquakes and groundwater pumping, and glacier thickness is now possible. One of the most challenging and potentially rewarding frontiers of geodetic science is the collection of active remote sensing data using unmanned aerial vehicles (UAVs), such as drones. These platforms offer several advantages over their spaceborne counterparts. The vehicles can stay aloft up to several days above a region of interest performing wide area surveys or repeat-track analysis. Revisit intervals can be tailored for the phenomenon of interest, and UAVs can be used to rapidly respond to major events. Moreover, the aircraft and instrument packages for UAVs can be designed and deployed much more rapidly than their spaceborne counterparts. Lower altitude means less power is required for active sensors, and a shorter atmospheric path between the aircraft and the ground target increases the instruments' accuracy. One could also envision, for example, fleets of autonomous aircraft flying in formation to synthesize a single large-aperture radar for wide-area topographic mapping and change detection.

Achieving these goals for UAVs requires high-accuracy, real-time navigation, both for public safety and for the accuracy of the data these vehicles collect, and would place high demands on the geodetic infrastructure. Present-day real-time navigation requirements for (manned) aircraft-based LiDAR are 1 meter and, for post-processing, 0.1 meter. However, as the LiDAR range precision is improved, real-time navigation requirements for high-precision surveys will likely be better than 1 meter, and the relative post positioning errors may need to be below 5 millimeters. Such high positioning precision will require a relatively dense array of ground GPS receivers.

Soil Moisture Mapping

Society relies heavily on weather and climate forecasts to improve agricultural yields and to mitigate the impact of drought and extreme weather events. Chapter 3 discusses how the geodetic infrastructure contributes to innovative weather forecasting methods. Accurate measures of how much water is being stored in the soil can further improve those forecasts. The satellites developed specifically for this task (European Soil Moisture and Ocean Salinity (SMOS) and U.S. Soil Moisture Active and Passive (SMAP) satellites) are scheduled to be launched in the next decade, but these missions have limited lifetimes, do not measure soil moisture in real-time, and only repeat their ground sampling every 3–5 days.

Soil moisture satellites use radars that illuminate and measure the energy that is reflected by the land surface. They do this by taking advantage of the fact that wet soil interacts with the radar signal differently than dry soil. One of the challenges for soil moisture satellites is that they rely on calibration and validation from ground measurements (see Chapter 3). Ground measurements of soil moisture also are important because they illuminate variations in soil moisture on the local scale and provide a level of temporal sensitivity that is not available from satellites.

The best calibration for soil moisture satellites will come from the deployment of thousands of sensors around the globe. The global GNSS/GPS infrastructure may offer some of these calibration points. Larson et al. (2008) demonstrated that the GNSS/GPS signals that are reflected by land surfaces could be used to measure changes in soil moisture near continuously operating GNSS/GPS sites (see Chapter 4). The GNSS/GPS reflections sense the top layer of the soil surrounding the antenna in a region of approximately 1,000 square meters. This large spatial coverage is more beneficial than typical in situ measurements, which are sensitive to only about one liter of soil. In addition to showing a high correlation with traditional ground soil moisture instruments, using a pre-existing GNSS/GPS receiver would make GNSS/GPS-derived soil moisture data available without additional cost. Since GNSS/GPS data are downloaded frequently, it also means the soil moisture data would be available for near-term climate modeling and weather forecasting.

Precision Agriculture

The use of geodetic technology for operating farm machinery, using the collection of techniques known as precision agriculture, is rapidly growing in the United States. Precision agriculture has agronomical, economical, and environmental benefits. These techniques can save on crop inputs by optimizing the application of synthetic fertilizer and crop seed and can aid in crop protection and irrigation. Fertilizer, seed, and other products can be applied to fields with no skips, overlap/over-application, or deposition onto unwanted areas, thereby reducing waste and increasing yield. In addition, precise placement of seed can minimize tire/track compaction of the soil and eliminate crop trampling. When combined with leaf-sensing technology and remote sensing, post-emerge crop protection products such as pesticides can be applied on a variable-rate basis to meet the specific needs of a crop as it matures. Precision agriculture techniques also aid harvesting by allowing farmers to accurately apply "burn-down" products. These products hasten the ripening of grain, promoting even grain maturity across entire fields and thereby reducing the potential for "green," or immature, crop to enter the harvest chain; reducing the likelihood of crop spoilage while in storage; and reducing artificial drying costs, which will result in less use of propane or natural gas.

Currently, precision agriculture practices are not directly based on the global geodetic infrastructure, but on correction systems like the Wide Area Augmentation System, which uses local correction services. These local services are used across the U.S. corn, cotton, sorghum, and soybean crop belts to provide the required accuracy. Developing the global geodetic infrastructure to the point where it could support real-time positioning at an accuracy of 1 centimeter would have several advantages for precision agriculture. First, the infrastructure would be accessible from any location without the need to develop and maintain local infrastructure. Second, it would increase the potential to integrate straightforwardly multiple sources of information (e.g., remote sensing imagery and terrain/topography) in a GIS-based framework. Integration with agriculture management systems also could provide automation for increasingly complex farm and crop management, including crop rotation and/or crop interlacing, and improve management of polyculture farms for sustainability (Box 2.2).

Coastal Wetland Monitoring

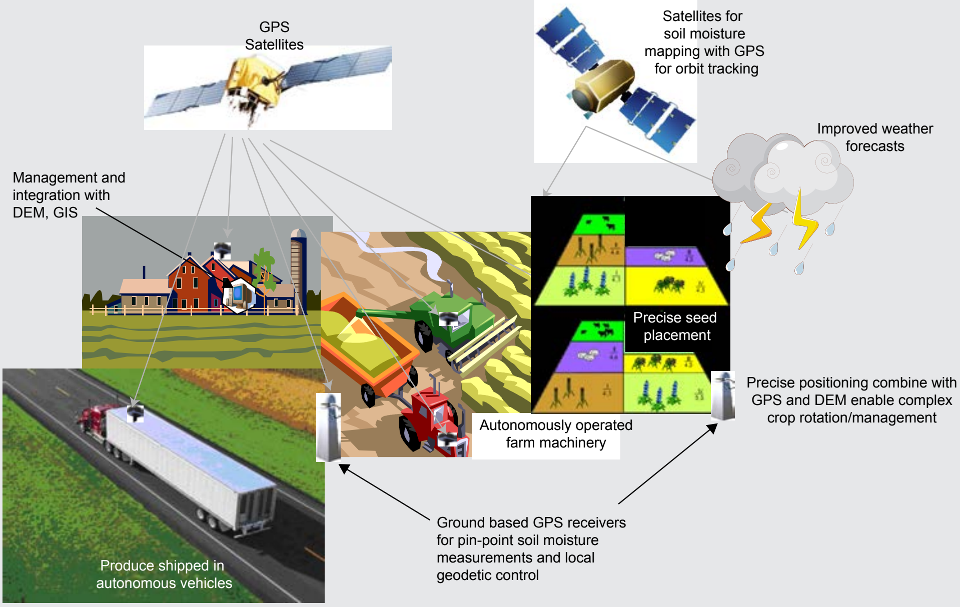
Coastal wetlands serve many important roles. They serve as a buffer to absorb storm surge when storms make landfall; they also have important ecological functions. But, they are increasingly vulnerable to sea-level change; to subsidence caused by pumping of groundwater, oil, and natural gas; and to other environmental impacts of increasing population densities near the coast. In these areas, centimeter-level changes in elevation or sea level can have dramatic consequences for coastal resources and can mean the difference between extensive wetland habitats and open water. Determining accurate elevations within coastal wetlands improves the understanding of processes affecting wetland dynamics, land loss, and the effects of pollution, such as from oil spills.

Obtaining accurate vertical measurements in coastal wetlands has been problematic for scientists, since instrumentation and techniques that work on either solid ground or over open water are difficult to use in this important transition region. As a result, the surface of the water within wetlands has been difficult to monitor with any accuracy or spatial/temporal resolution. However, there are several developments on the horizon that could contribute to this important societal need.

The GRAV-D survey proposed by the NGS (see "Improved Floodplain and Inundation Maps" above) will improve our knowledge of the relative water level (and its changes) for coastal wetlands by taking repeated airborne gravity surveys in these regions. The GRAV-D surveys would improve significantly the currently inaccurate gravity models in the coastal zone. NGS is also working with partners to extend the national network of passive survey control marks ("bench marks") into the coastal zone.

In addition, the geodetic Interferometric Synthetic Aperture Radar (InSAR) and LiDAR techniques are capable of providing high-resolution observations of surface water-level changes in wetlands and floodplains (Wdowninski et al., 2008; Yang, 2005). The temporal resolution of this technique, as in other applications of InSAR (see Chapter 3), is currently limited by the availability

BOX 2.2
Autonomous Farming



Conceptual illustration of the "farm of the future" that could be enabled by the geodetic infrastructure. The global geodetic infrastructure would provide precise positional capability anywhere in the world at all times for precise agriculture applications, including automated farm machinery and precision seed placement. Soil moisture would be monitored by remote sensing and ground-based GNSS/GPS integrated into GIS, providing accurate management of irrigation. Local GNSS/GPS networks would improve local weather forecasts. Accurate terrain, elevation, and land cover information, integrated with GIS, would enable complex crop management. Farm produce would be transported away in autonomously navigated vehicles.

of InSAR data for the specific regions being monitored. In addition to accurate measurements of surface height, InSAR over wetlands can detect patterns in the water flow. This application will extend significantly the concept of "geodetic imaging" (see section "Future Scientific and Technological Breakthroughs") for better monitoring of coastal wetlands.

FUTURE SCIENTIFIC AND TECHNOLOGICAL BREAKTHROUGHS

The global geodetic infrastructure, even at its current level, has enabled a wealth of applications that have commercial, scientific, economic, national security, and agricultural benefits. To a great extent, this infrastructure has been developed for science or military applications, but the accuracy and robustness of the infrastructure enables society at large to benefit. One of the catalysts for broadening the accessibility of the infrastructure has been the adoption of standards for data acquisition, data formats, data analysis, and data products. These standards have been developed in large part by the international scientific community and have proven so successful that they have been adopted by agencies of the U.S. government and by GNSS/GPS equipment manufacturers.[4] In addition to broadening the accessibility of the infrastructure, these standards enable the scientific research that has led to the order-of-magnitude per decade improvement in geodetic accuracy. As the goal now shifts to applications that require improved spatial and temporal resolution with low latency (real-time geodetic imaging), the demands on the geodetic infrastructure and the importance of universal standards will continue to increase. Many potential future breakthroughs, like fully autonomous transportation systems, are possible only with a highly robust geodetic infrastructure that provides accurate data products in real time in a universally accepted reference system.

As famously stated by Niels Bohr, "[p]rediction is very difficult, especially about the future" (Ellis, 1970, p. 431). Nonetheless, it is legitimate to ask whether the order-of-magnitude-per-decade performance improvement rate for precise geodesy is sustainable in the foreseeable future. Although it is questionable whether improving the ITRF to achieve a millionth of a meter accuracy is a sensible question, it is certainly clear that there is much room for advancement in space and time resolution for geodetic data. The challenges to achieving real-time geodetic imaging, however, are readily apparent. Consider doubling the horizontal resolution of any geodetic data set and updating it twice as often as in the past, and it is soon realized that this calls for acquiring, storing, processing, and analyzing eight times as much data. If users desired to improve the spatial resolution of the commonly used SRTM digital elevation datasets from 90 meters globally to 10 meters, they would have to be ready to deal with a dataset approximately 100 times larger. If capturing changes with time is of the essence, this factor can easily grow to be 1,000 times or more. Improving the vertical accuracy from 15 meters to 1.5 meters would not directly impact the data set size, but the information needed to generate the data set would increase by another factor of 100 to 1,000. With these improvements, data volumes could grow by a million-fold compared to today's volumes. The fact is, LiDAR imaging of critical areas such as coastlines or earthquake faults is already pushing well beyond these limits in all four dimensions (see Wdowinski and Erriksson, 2009).

Perhaps further into the future it may be feasible to deploy very large (100-meter inflatable) radar antennas in geosynchronous orbit, permitting real-time InSAR imaging of the Earth's deformation on a continental scale ("InSAR everywhere all the time," Zebker, 2005). We also can imagine a steady microwave illumination of the Earth's surface from geostationary or even lunar radar transmitters. With superior time transfer capabilities, bistatic radar imaging becomes possible: small inexpensive receivers in low Earth orbit could image the Earth's surface interferometrically, much as optical sensors image the sun-illuminated surface now, except that this would be an all-weather capability.

SUMMARY

The applications reviewed in this section represent just a few of the current and future benefits of the geodetic infrastructure. Of course, it would not be unexpected if any predictions, short- or long-term, were far outstripped by reality. As the technology continues to mature, it becomes ever more accessible to an increasingly wide group of scientists, engineers, and entrepreneurs. Developers and users alike will increasingly be able to take advantage of geodetic methods, techniques, and systems without specialized knowledge of geodesy or related fields.

All the advances reviewed in this chapter are and will be made possible by an underlying geodetic infrastructure that is robust, reliable, and accurate. This infrastructure includes not only measurement systems and networks discussed in Chapters 3–5, but also the global services that analyze and maintain standards for these systems, as well as the analysis that knits together these systems.

Providing the infrastructure capable of supporting the societal needs of today and the future is the great challenge for the field of geodesy. In the next section, the committee provides recommendations for meeting this challenge.

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[4] The NGS and the Federal Geodetic Control Subcommittee develop federal standards for geodetic control surveys.

3

Geodesy Requirements for Earth Science

Precise geodetic infrastructure enables ground- and space-based observations that are critical to a wide array of scientific disciplines, including seismology, geodynamics, climate science, hydrology, oceanography, meteorology, and space weather. Geodetic observations, for example, allow us to measure and monitor gradual changes in tectonic plate movement, sea level rise, glacial ice melting, and aquifer depletion. Similarly, the geodetic infrastructure provides the foundation for numerous applications with broad societal and commercial impact, from early warning systems for hazards to intelligent transportation systems (Figure 3.1). Over time, the precision and timeliness of these applications has improved, with operational applications now routinely working at accuracies only recently achievable, while the scientific applications are approaching the part-per-billion accuracy level and near-real-time operations. The scientific questions that are being asked about how the Earth system works and what can be predicted for the future continue to drive ever more stringent requirements for geodesy.

The demand for geodetic observations will continue to grow as we move from global to regional forecasts of climate change impacts, from manual to autonomous systems that require more precise positioning in real time, and from point positioning to geodetic imaging. Given the breadth of scientific and societal applications, this chapter is not intended to be comprehensive, but rather to highlight only a sampling of the benefits that high-precision geodetic infrastructure provides for Earth science and the nation.

SOLID EARTH DYNAMICS

Geodynamics

Plate Motion and Tectonics

Nothing on Earth's surface is fixed, and enormous pieces of the crust are being ripped apart or forced into collisions with each other by the movement of the mantle below, causing earthquakes, volcanoes, and mountain building. Earth's crust is currently considered to consist of approximately

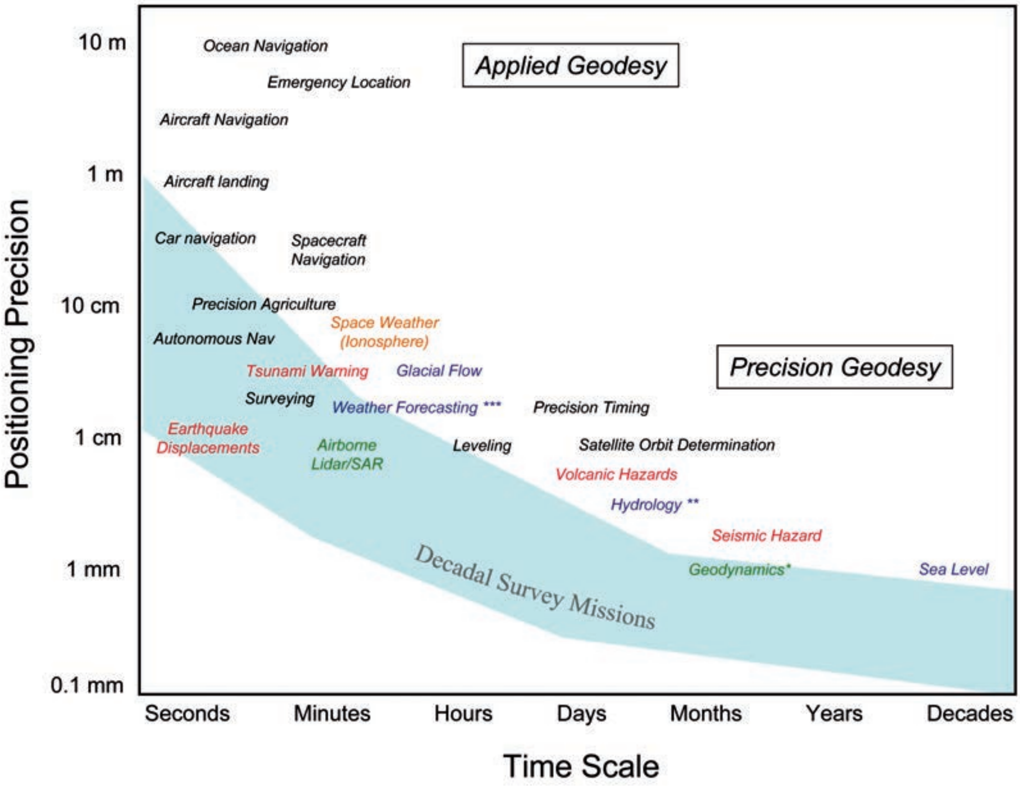


FIGURE 3.1 This schematic plots the precision of current geodetic applications as a function of the required time interval. The most demanding applications at the shortest time intervals include GNSS/GPS seismology and tsunami warning systems. At the longest time intervals, the most demanding applications include sea level change and geodynamics. Note that the positioning scale is in powers of 10 and that range of geodetic applications spans approximately nine orders of magnitude in the time scale. Consistency in connecting the longest to the shortest time scales requires an accurate and stable global terrestrial reference frame, which drives the most stringent requirements on the geodetic infrastructure.

* Plate motion, plate deformation, mountain building, mass transport, ice-sheet changes (using loading motion and gravity changes observed from space).

** Vertical surface motion from GNSS/GPS and InSAR for ground water management; water redistribution is monitored from space based on gravity measurements).

*** Water vapor and other meteorological information from GNSS/GPS ground stations and radio occultations in space.

52 "rigid" plates (14 major plates and approximately 38 minor plates) that slowly drift across the surface of the planet, changing speed and direction on million-year timescales (McKenzie and Parker, 1967). The edges of the plates undergo a variety of non-rigid and unsteady motions, which are classified according to the direction of relative plate motion across the boundary. Divergent boundaries form the mid-ocean ridges that encircle the planet like seams on a baseball. Here, plates spread apart and the void is filled from below by hot material. Convergent plate boundaries form the deep ocean trenches where the cooled plates subduct back into Earth's mantle. The largest earthquakes occur when these subducting plates slip past each other after sticking together for a period of 300–1,000 years (*stick-slip* behavior). Transform boundaries (which cause *strike-slip* motion) mainly occur in the deep oceans, although they occasionally cut across the continental areas. A

prominent example of a transform boundary is the San Andreas Fault, which undergoes strike-slip motion on 100–1,000 year time scales, resulting in destructive earthquakes. Mountainous areas on the continents, such as the Himalayas and the Alps, are formed by convergent motion (collisions) between continental plates. However, where an oceanic plate collides with a continental plate, such as the North American Cascades, major earthquakes and volcanism can be expected.

Global-scale geodetic measurements of plate motions from Very Long Baseline Interferometry (VLBI) and Satellite Laser Ranging (SLR), based on less than a decade of data, show remarkable agreement (at the 3–5 millimeters per year level) with plate motions derived from the 1–3 million year average rates derived form the geological and geophysical data (Herring et al., 1986; Carter and Robertson, 1986). Some tectonic plate studies, however, drive a requirement for a higher level of accuracy. For example, the boundaries of the plates have narrow regions where shorter timescale plate-to-plate interactions are important. These include areas of high crustal strain (Figure 3.2), which result in destructive earthquakes and volcanoes. In addition, the plates do not behave exactly rigidly, and the measure of horizontal intraplate deformation could be associated with the thermal contraction of the cooling oceanic lithosphere. This plate shrinkage has recently been detected at the 3 millimeter per year level (Kumar and Gordon, 2009).

Post-Glacial Rebound

During the last Ice Age, vast ice sheets up to 4–5 kilometers thick lay over the Hudson Bay region in northern Canada and across much of Scandinavia. The amount of ice locked up in the ice sheets at the time was enough to cause global sea levels to lie 100–150 meters below their present levels (Peltier, 2004). The pressure from that ice load on Earth's crust caused the underlying mantle to be depressed. When the ice melted, starting roughly 20,000 years ago and continuing until approximately 10,000 years ago for Canada and Scandinavia, Earth began to rebound. That rebound (also known as glacial isostatic adjustment) continues today because Earth is viscous, and it takes time for a viscous body to fully respond to the removal of a load. Observations of the rebound rate provide information about Earth's viscosity profile, which plays a key role in determining the pattern and vigor of convection in Earth's mantle that drives plate motion and causes earthquakes

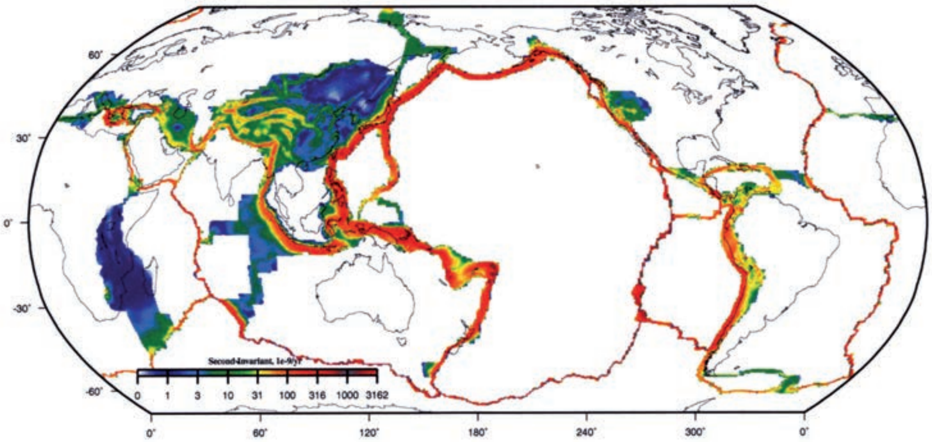


FIGURE 3.2 Geologic, geodetic, and earthquake data help determine the zones on Earth where the crustal motion diverges from rigid plate motion. Areas of high strain, in red, experience increased earthquakes and volcanoes. SOURCE: Kreemer et al., 2000.

and volcanic activity. The characteristics of the ancient ice sheets are also of interest because they provide insight into how the cryosphere has responded to dramatic changes in climate in the past.

It is only through geodetic observations that the present-day rebound can be observed as it actually happens. There are two types of relevant geodetic observations. One involves the measurement of surface uplift rates at points near the locations of the ancient ice sheets. Measurements of this type are now usually made with GNSS/GPS (see Lidberg et al., 2007; Sella et al., 2007), though VLBI observations have been used as well (Heki, 1996; James and Morgan, 1990; Mitrovica et al, 1993). The other type of geodetic observation is time-variable gravity. The ongoing rebound leads to changes in Earth's mass distribution, which in turn cause Earth's gravity field to evolve over time. The gravity field over northern Canada, for example, is steadily increasing in strength as mass in the underlying mantle flows in sideways from surrounding regions, pushing Earth's surface upwards. Those gravity changes are best seen in satellite gravity data, such as from LAGEOS (Cox and Chao, 2002; Cheng and Tapley, 2004) and, especially, GRACE (see Box 3.1) (Paulson et al., 2007; Tamisiea et al., 2007). These space-based gravity measurement techniques use the geodetic infrastructure to determine an accurate reference against which to measure the small post-glacial rebound motions; the geodetic techniques also provide the data containing important geophysical signals.

Earth Orientation (Length of Day, Polar Motion, and Nutation)

The direction of Earth's rotation axis and the rate of rotation about that axis vary with time (for general reviews, see Dehant, 2007; Gross, 2007; Lambeck, 1980). As described in Chapter 1, the change in the rate of rotation causes a small change in the length of day. The motion of the rotation axis itself is described by *polar motion* and *nutation*. Polar motion refers to motion of the axis relative to fixed points on Earth's surface, while nutation refers to motion with respect to fixed objects in space. For the past several decades, the determination of Earth's orientation has been based on observations from the global network of VLBI, GNSS/GPS, and SLR stations, and the results are critically dependent on reference frame accuracy. The orientation and rotation rate of the reference frame used when analyzing these geodetic measurements are directly related to the rotational parameters used for geophysical interpretation. Consequently, reference frame errors can map directly into errors in that interpretation.

Earth Tides

The tidal force from the sun and moon causes tides in the solid Earth, just as it does in the ocean. The periods are the same, and even the amplitudes are similar: tidal displacements in both the solid Earth and the open ocean are on the order of several tens of centimeters. Solid Earth tides are best observed using geodetic measurement techniques. Information on tidal deformation of Earth at global-scale wavelengths provides unique information on Earth's structural parameters.

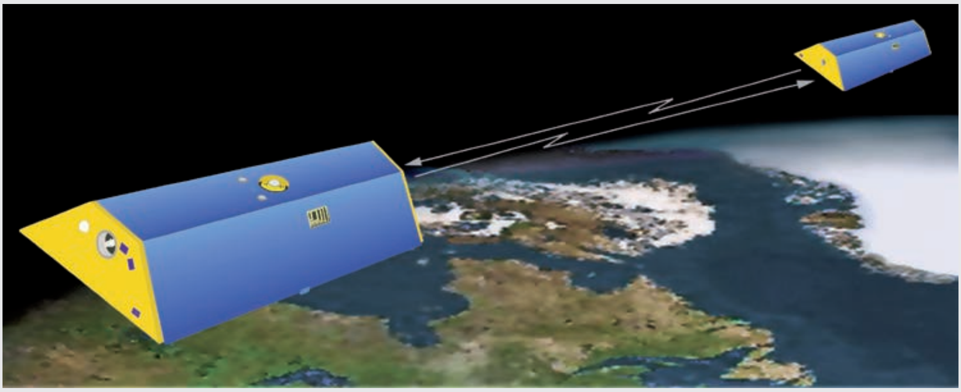
Natural Hazards

Volcanoes

There are 170 volcanoes in the United States, of which at least 65 are active or potentially active. The U.S. Geological Survey (USGS) Volcano Hazards Program routinely monitors volcanoes using a variety of methods designed to detect and measure changes caused by the underground movement of *magma* (molten rock). Rising magma typically will: trigger earthquakes and other seismic events; cause swelling or subsidence of a volcano's summit or flanks; and lead to the release of

BOX 3.1
The Gravity Recovery and Climate Experiment (GRACE)

The Gravity Recovery and Climate Experiment (GRACE), a joint NASA/Deutsches Zentrum für Luft- und Raumfahrt (DLR) mission to map the time-variable and mean gravity field of Earth, was launched on March 17, 2002 (Tapley et al., 2004a,b). Using an extremely high-precision inter-satellite ranging system, subtle variations in Earth's gravity field are detected through changes in the distance between the two satellites (since each satellite detects slightly different gravity effects due to their separation of approximately 200 kilometers). This has made it possible to observe seasonal, long-term, and climate-driven changes in Earth's mass distribution at a resolution of several hundred kilometers. In addition, knowledge of the static component of Earth's gravity field has been improved by orders of magnitude, providing a global geoid model accurate to the centimeter level at 200-kilometer resolution.



The twin GRACE satellites using a dual one-way K-band (20–40 GHz) ranging system to observe changes in their relative distance to the few micron level. The scale is for illustration purposes only; the actual separation distance is kept close to 200 kilometers. SOURCE: John C. Ries, The University of Texas Center for Space Research.

volcanic gases from the ground and vents. By monitoring these phenomena, scientists sometimes can anticipate an eruption days to weeks in advance or remotely detect explosive eruptions and *lahars* (a mixture of water and rock fragments that flow down the slopes of a volcano). Successfully monitoring and forecasting Mount Pinatubo's cataclysmic eruption in 1991, for example, prevented property losses of more than $250 million (Newhall et al., 2005).

GNSS/GPS receivers and Interferometric Synthetic Aperture Radar (InSAR) are the main geodetic tools used for monitoring volcanic surface deformation, as well as earthquake deformation (discussed below). GNSS/GPS receivers can be set up at strategic locations around a site to stream measurements continuously. InSAR, on the other hand, can uniquely map and resolve surface deformation over a wide range of spatial scales that is not possible with GNSS/GPS (see Figure 3.3). The research community in the United States currently relies on InSAR data collected by several radar satellite missions, including those flown by the European (ERS-2, Envisat), Canadian (Radarsat-1) and Japanese (ALOS) space agencies (see Table 4.1). Combining the high-spatial-resolution InSAR map with high-temporal-resolution GNSS/GPS point measurements provides the full four-dimensional picture of volcanic deformation. An unexpected result of using InSAR and GNSS/GPS systematically to study volcanoes in Alaska and the western United States is the

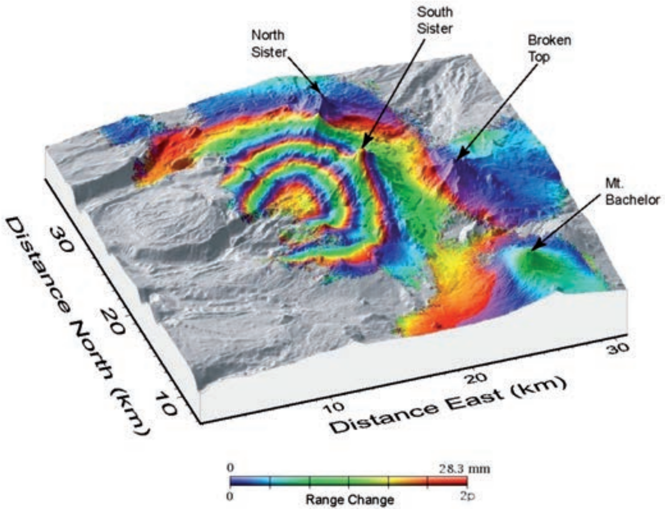


FIGURE 3.3 An InSAR-defined area of uplift near the Three Sisters cluster of volcanoes in central Oregon, where each concentric circle of red corresponds to approximately 28 millimeters in deformation. This deformation, which does not lie directly beneath any volcano, is in an area where the most recent eruption occurred 1,500 years ago. Uplift of the ground's surface, which began in 1997, reached 15 centimeters at the center of the "bull's eye" pattern in 2001. Subsequent GPS monitoring shows that uplift continues at a steady pace, suggesting that it is produced by upward movement of magma (intrusion). The InSAR pattern places the depth of intrusion at 6–7 kilometers. SOURCE: Wicks et al., 2002. Courtesy of the American Geophysical Union.

discovery that volcanoes once thought to be dormant are actually undergoing gradual deformation and may eventually erupt. Because volcanic deformation tends to be a slow process taking decades to centuries between eruptions, InSAR and GNSS/GPS measurements must be tied to decades of data from a stable terrestrial reference frame with better than 5 millimeter precision.

Earthquakes

The sudden release of energy along a major earthquake fault is one of the most destructive forces of nature. Predicting earthquakes depends on our ability to understand the *earthquake cycle,* which requires geodetic measurements of Earth's crustal motion between seismic events. At depths greater than 20 kilometers, the North American and Pacific plates slide freely past one another. Shallow fault zones, however, are colder and more brittle and undergo stick-slip behavior, in which the shallow surfaces of the fault remain locked for periods sometimes lasting hundreds of years because of friction and surface imperfections. Eventually, the tectonic stress exceeds the fault strength, causing the plates to slip past each other (a *coseismic* event).

Recently, scientists discovered that slips can be either fast and destructive or slow and minimal. An example of short-term transient slow slip behavior at a subduction zone is the phenomenon of Episodic Tremor and Slip (ETS) (Rogers and Dragert, 2003; see Figure 3.4). ETS, as observed along the northern Cascadia Subduction Zone, has been defined empirically as repeated, transient ground motions at a plate margin. Prior to the discovery of ETS, geologists thought the Cascadia coastal margin was squeezed landward in a continuous, steady fashion. It is inferred that the deeper plate interface also undergoes a stick-slip behavior, but over a much shorter time-scale than the earthquake cycle. The relationship between ETS and regional earthquakes is not yet clear, but it is conceivable that an ETS episode could ultimately trigger a large earthquake.

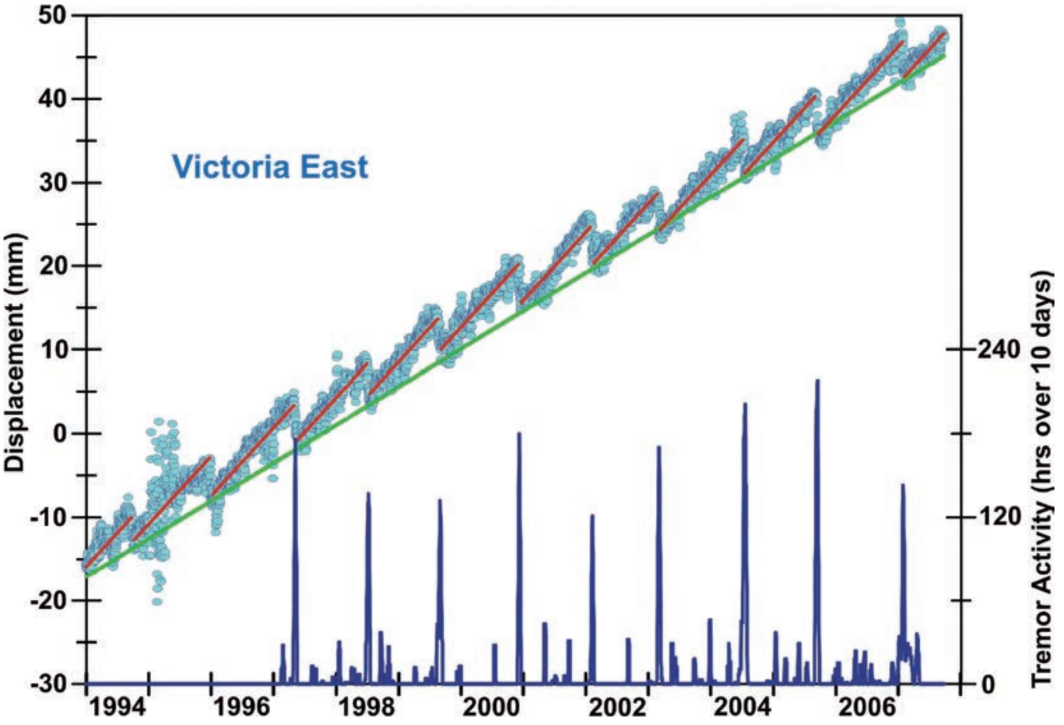


FIGURE 3.4 GNSS/GPS and seismic data as observed on the Cascadia Subduction Zone. The plot demonstrates an example of Episodic Tremor and Slip (Rogers and Dragert, 2003), a phenomenon of short-term transient slow slip behavior at a subduction zone. Each blue circle in the plot indicates the daily change of the east-west position of the Victoria GPS station relative to the interior of the North American Plate. The green line shows the long-term linear motion over the 14-year period. The red line shows that for roughly 15 months this deeper fault zone resisted slip but then slipped several centimeters over a period of weeks, resulting in a characteristic sloped saw-tooth time series for the longitude component of coastal GPS stations. SOURCE: Rogers and Dragert, 2003.

Fast ruptures generate elastic waves that propagate outward and destroy buildings. Slow ruptures, which could be detected only recently using GNSS/GPS receivers, can release the tectonic stress over periods of several days to weeks. Following an earthquake, the fault continues to slip, generating aftershocks. This *postseismic* deformation can last for tens of years.

Some scientists also hypothesize that there is a short period of concentrated deformation just prior to a major earthquake, although this period of *preseismic* deformation is poorly documented. Modern space-based geodetic measurements, such as GNSS/GPS and InSAR, have recorded all but the preseismic elements of the earthquake cycle. With the new tools geodesy offers, however, scientists are beginning to understand the earthquake process and may someday be able to provide useful earthquake forecasts.

Accurate and robust measurements of subtle secular and precursory deformation are the new frontiers in crustal deformation studies and are pivotal for natural hazards research. These measurements can be accomplished with GNSS/GPS, InSAR and Aircraft Laser Mapping (ALM). The Plate Boundary Observatory, part of the National Science Foundation's EarthScope project, consists of 1,100 strategically distributed GPS receivers, as well as borehole seismometers, tiltmeters, and laser strainmeters installed along the western United States (see Figure 3.5). This geodetic observatory continuously monitors the strain field that results from the deformation of the active boundary zone

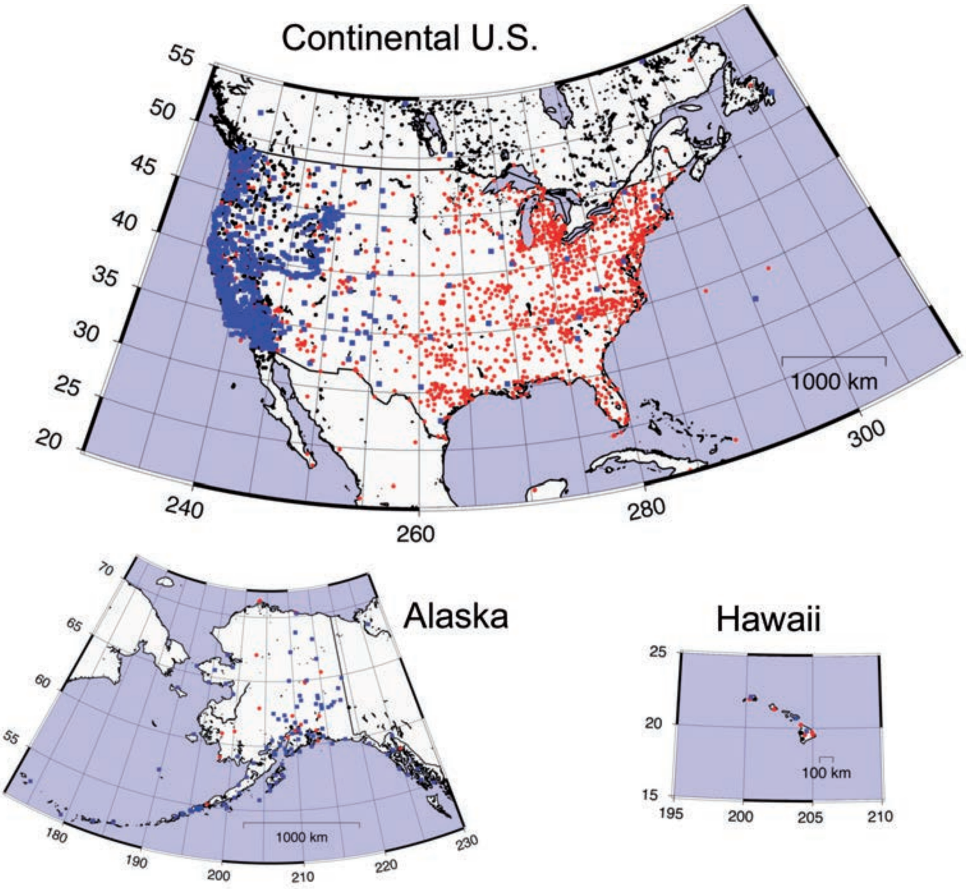


FIGURE 3.5 Map showing the continuously operating GPS stations in the United States. Blue dots are Plate Boundary Observatory (PBO) sites installed by the NSF. Red dots are Continuously Operating Reference Stations (CORS), which are installed and operated by a variety of federal, state, and local agencies and some private companies and whose data is available through the National Geodetic Survey. Black dots are other sites that do not fall into either the PBO or CORS groups. Some of the PBO sites are also CORS sites. SOURCE: Courtesy of Thomas Herring, Massachusetts Institute of Technology, using Generic Mapping Tool (GMT developed by Paul Wessel and Walter Smith). Graphic generated on May 28, 2010, using NOAA/NGS CORS data acquired from CORS website: http://www.ngs.noaa.gov/CORS/sort_sites.shtmll.

over multiple time scales. InSAR is a highly complementary and synergetic technique to the Plate Boundary Observatory's GPS network, because it can generate continuous high-resolution maps of surface strain over large areas in any weather condition day or night, typically on monthly timescales. Figure 3.6, based on InSAR data, illustrates the ground deformation resulting from the 7.9-magnitude Wechuan earthquake in China. Precise orbits and ionospheric delay corrections are needed to construct a seamless deformation map from multiple swaths. ALM offers a third geodetic method for estimating seismic hazards. The B4 project, for example, has mapped the entire San Andreas fault system at 1-meter spatial resolution and 0.1 meter vertical accuracy. Studies of the morphology of the fault zone, such as those combining offset stream channels with geochronology, provide critical information on the recent slip histories of specific faults. This information can be compared with the strain accumulation rate measurements from geodesy to estimate when the next major rupture is most likely to occur. In addition, mapping that is done before the next major rupture (hence, "B4") will

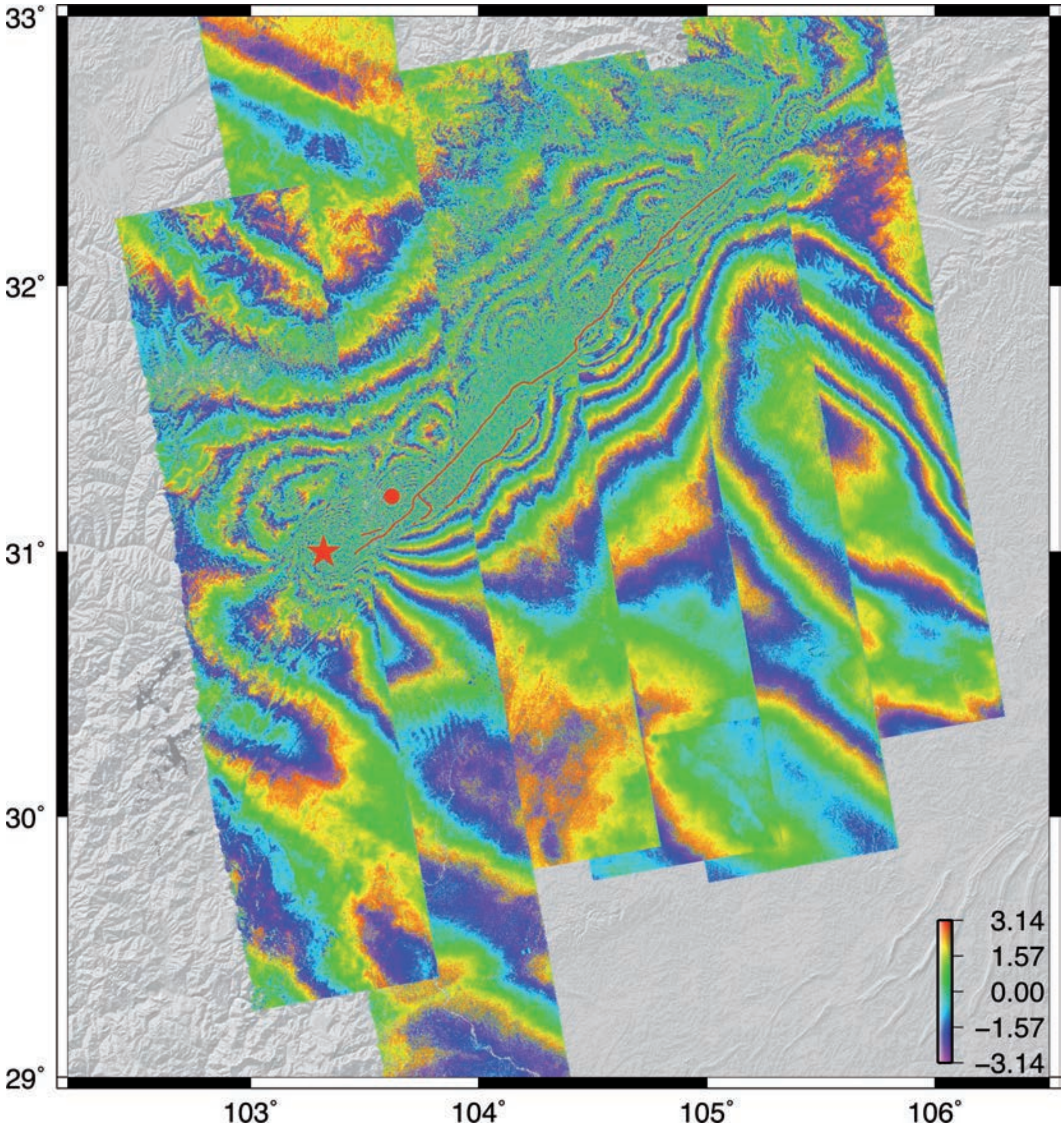


FIGURE 3.6 Ground deformation from ALOS L-band interferometry (each concentric color "fringe" corresponds to approximately 10 centimeters of displacement) due to the 7.9-magnitude Wenchuan earthquake, which occurred on May 12, 2008, along the western edge of the Sichuan Basin in China. Shaking from the 270-kilometer-long rupture destroyed thousands of structures, killing nearly 70,000 people and leaving more than 4.8 million homeless. ALOS-derived ground deformation maps were available within a few days after the rupture in order to assess the extent of the damage zone, as well as to provide an estimate of regions of increased seismic risk. SOURCE: David Sandwell, University of California–San Diego.

provide the reference surface for assessing the very-small-scale deformation associated with a major rupture. The geodetic infrastructure for earthquake hazard monitoring with GNSS/GPS, InSAR and ALM would require better than 5-millimeter accuracy over 10 years.

Landslides

Landslides include a wide range of ground movements, such as rock falls, deep failure of slopes, and shallow debris flows (USGS, 2010). Although gravity acting on an over-steepened slope is the primary reason for a landslide, there are other contributing factors such as soil saturation by rainfall or snowmelt, earthquakes, volcanic eruptions, and stress induced by man-made structures. Understanding and mitigating landslide risk involves identifying areas of susceptibility (see Radbruch-Hall et al., 1982), determining which potential landslides are active, and deploying ground-based investigations in area of high risk and/or active slide areas.

A promising method for identifying active landslide areas greater than about 200 meters is to use InSAR. Newer Japanese InSAR satellites operating at a longer wavelength (L-band) may make it possible to perform a global inventory of active landslides, even including those on vegetated surfaces. When the location of an active slide has been determined, ground-based methods, such as Light Detection and Ranging (LiDAR) mounted on tripods or aircraft, can be deployed to obtain “bare Earth” surveys (see Figure 3.7). The three-dimensional coordinates of the laser points can be used to determine the volume of the material involved in the landslide, as well as surface roughness and slopes of the slide and surrounding terrain.

Floods

Many natural processes, including hurricanes, weather systems, and snowmelt, can cause floods. Floods can also be caused by failure of levees and dams and inadequate drainage in urban areas.

FIGURE 3.7 These false-color geodetic images of a landslide near Flathead Lake, Montana, were made from airborne LiDAR data collected by the NSF National Center for Airborne Laser Mapping (NCALM). Laser shots passed through openings in the forest and reached the ground, allowing a filter to be used to remove the returns from the trees and reveal the landslide, which is not normally visible to the eye or a camera. The white scale bars are 500 meters in length. SOURCE: Ramesh Shrestha, National Center for Airborne Laser Mapping (NCALM), University of Houston; see also Carter et al., 2007.

On average, floods kill more than 100 people in the United States each year and cause billions of dollars in property damage (Figure 3.8). Land surface elevation defines the direction, velocity, and depth of flood flows, while subsidence measurements indicate how these values will change in the future. Elevations of individual streams and rivers traditionally have been mapped by land surveying. However, because Federal Emergency Management Agency (FEMA) floodplain mapping must cover nearly one million miles of the nation's streams and shorelines, land surface elevation data are mostly derived from mapped sources, not from land surveying (NRC, 2007b). Land surface elevation information is combined with data from flood hydrology and hydraulic simulation models to define the base flood elevation, which indicates the extent of inundation. The creation of floodplain maps is an important part of the National Flood Insurance Program, as these maps determine flood insurance requirements. FEMA is undertaking an ambitious five-year program to update and digitize the nation's floodplain maps.

Flat terrain in coastal zones and river flood plains are particularly flood-prone. According to the National Research Council (NRC) report *Elevation Data for Floodplain Mapping* (2007b), "…elevation data of at least 1-foot equivalent contour accuracy should be acquired in these very flat areas, rather than the 2-foot equivalent contour accuracy data that the FEMA floodplain mapping standards presently require for flat areas." Achieving this 1-foot accuracy actually requires two geodetic measurements—the terrain elevation and the geoid height (see Chapter 1). The NRC

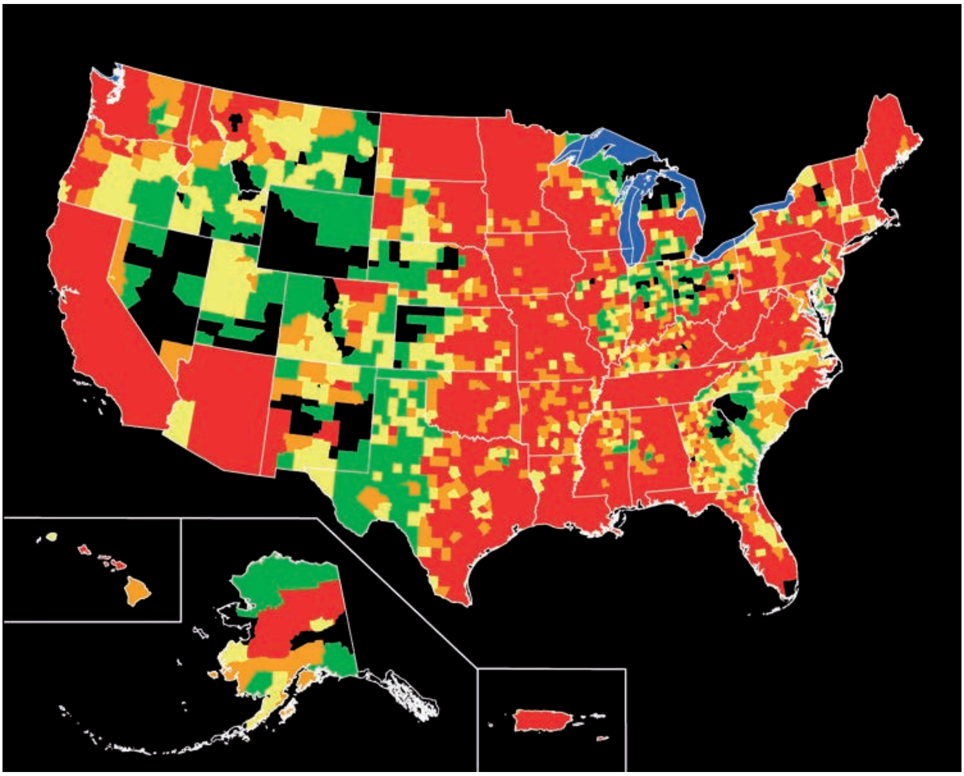


FIGURE 3.8 Presidential disaster declarations related to flooding in the United States, shown by county: Green areas represent one declaration; yellow areas represent two declarations; orange areas represent three declarations; and red areas represent four or more declarations between June 1, 1965, and June 1, 2003. Map is not to scale. SOURCES: FEMA; Michael Baker Jr., Inc.; the National Atlas; and the USGS (from http://www.usgs.gov/hazards/floods/).

committee examined three technologies for supplying elevation information: photogrammetry, LiDAR, and InSAR. LiDAR is capable of producing a bare-Earth elevation model with two-foot equivalent contour accuracy in most terrain and land cover types; a four-foot equivalent contour accuracy is more cost-effective in mountainous terrain, and a one-foot equivalent contour accuracy can be achieved in very flat coastal or inland floodplains. A seamless nationwide elevation database created at these accuracies would meet FEMA's published requirements for floodplain mapping for the nation. The second geodetic measurement needed to achieve the one-foot contour accuracy requirement is the geoid height. Water flows downhill with respect to the geoid, which coincides with mean sea level at the coastline, or zero elevation. The combined accuracy of the terrain elevation and geoid height is approximately 30 centimeters, so the geoid accuracy alone must be better than that. The latest high-resolution global geoid height model EGM2008 (see Chapter 4) is estimated to be accurate to 10 centimeters or better over most of the United States (Pavlis et al., 2008a), which meets the geoid height accuracy requirement.

Tsunamis

Some of the most catastrophic natural disasters result from tsunamis. Tsunamis are generated by rapid displacement of the ocean floor (Song et al., 2008). The largest tsunamis are generated by earthquakes, specifically *megathrust* earthquakes occurring at ocean trenches known as *subduction zones*, where tectonic plates converge. Such was the case for the Indian Ocean tsunami, which was generated by an estimated 9.1- to 9.3-magnitude Sumatra earthquake (Stein and Okal, 2005), killing more than 150,000 people and leaving millions more homeless in 11 countries (National Geographic News, 2005). Subduction zones that present the largest tsunami hazard risk in the United States are those of the Pacific Rim, Alaska, and Cascadia, which is off the coast of Oregon and Washington.

Understanding the mechanism for tsunami generation is the key to assessing where future tsunamis are likely to occur and to developing early warning systems. A tsunami warning system will require the installation of continuously operating geodetic GNSS/GPS networks, which stream data in real time, as well as data analysis centers capable of processing the data in near real time. As illustrated in Figure 3.9, by measuring the rapid horizontal displacement of a GNSS/GPS receiver near the coast of a subduction zone, scientists can infer how much slip has taken place during the earthquake at the interface of the tectonic plates. From models of how earthquakes deform Earth's surface (Wang, 2003), it is possible to predict how much energy is imparted to the ocean, and thus

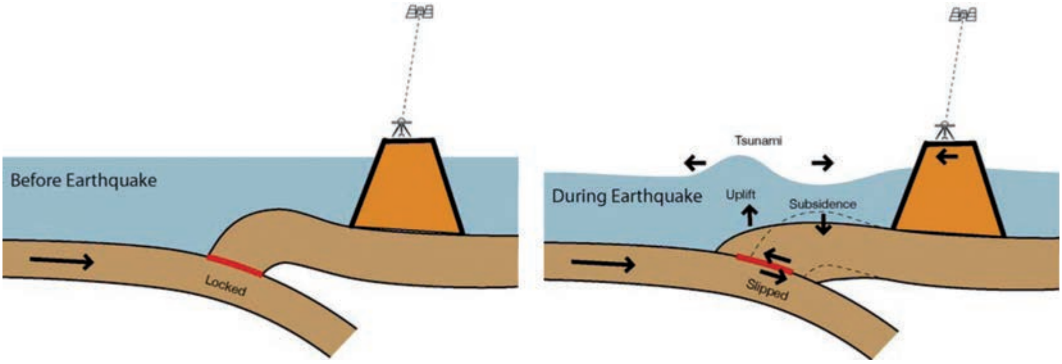


FIGURE 3.9 The largest tsunamis are generated by earthquakes occurring at ocean trenches, known as *subduction zones*, where tectonic plates converge. If the rapid horizontal displacement of a GNSS/GPS receiver near the coast of a subduction zone was measured and immediately available, it would be possible to infer how much slip had taken place and predict the likely size of the resulting tsunami. SOURCE: Blewitt et al., 2009.

predict the initial conditions of tsunami generation (Song, 2007). Ocean dynamic models can then be used to predict the ensuing tsunami (Titov et al., 2005). The key to this method is to be able to accurately measure the rapid horizontal displacement of GNSS/GPS receivers at the time of the earthquake.

Progress is being made to develop this capability. In the United States, the operational Global Differential GPS (GDGPS) System, developed by NASA's Jet Propulsion Laboratory (JPL) (Muellerschoen et al., 2001), is currently delivering real-time GPS corrections and is being developed into a system to enable real-time positioning with few-centimeter accuracy. Similarly, the International GNSS Service's Real-Time Pilot Project has the potential to demonstrate precise real-time positioning. In Canada, a pilot project is underway to measure, in real-time, the displacement of coastal GPS stations relative to stations further inland (Dragert et al., 2005). In Japan, the Earthquake Research Institute has developed tsunami warning buoys that are tracked by GNSS/GPS (Kato et al., 2005). In addition, Japan's Geographical Survey Institute already has GEONET, a very dense GNSS/GPS network with a real-time capability (Yamagiwa et al., 2006). In Europe, GeoForschungsZentrum has developed a concept known as "GPS Shield" (Sobolev et al., 2007), which also includes coastal GNSS/GPS stations as well as GNSS/GPS-tracked buoys to observe tsunamis directly. Accurate real-time GNSS/GPS geodesy requires near-real-time determination of GNSS/GPS satellite and clock parameters, a capability that is already under development by NASA at JPL. There is a need for interagency cooperation between NASA and NOAA to facilitate the transfer of this near-real-time information on tsunami-generating earthquake sources (NRC, 2011). A similar cooperation between NASA and USGS could facilitate rapid estimation of shaking and damage on land caused by large earthquakes. Figure 3.10 demonstrates that, had a real time capability for GNSS/GPS

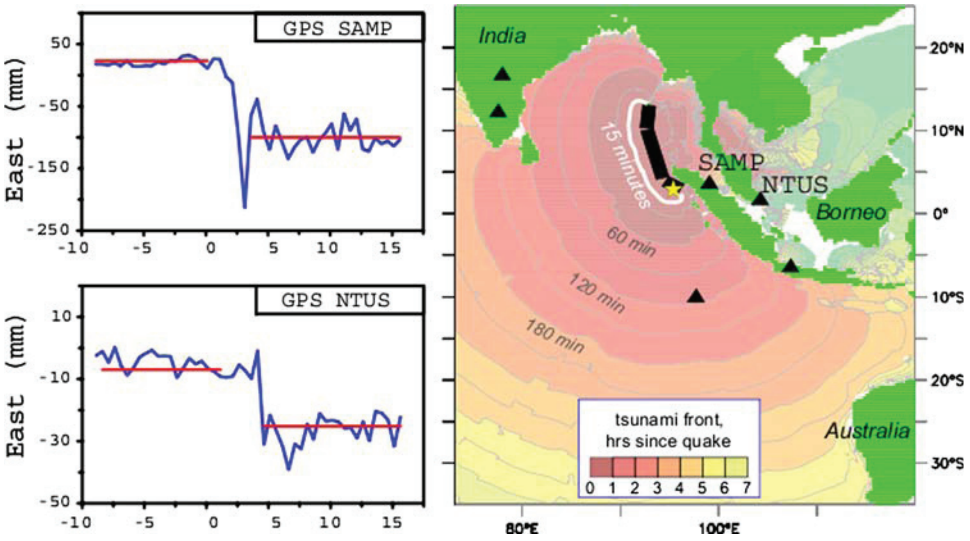


FIGURE 3.10 Permanent displacements observed using GPS during the estimated 9.1- to 9.3-magnitude Sumatra earthquake in 2004 demonstrated that, within minutes, permanent displacements can be resolved with approximately 10-millimeter accuracy. Sites SAMP and NTUS in the near-field (within approximately one rupture length) provide statistically significant offsets from which earthquake magnitude can be determined (left) to be in the range capable of generating an ocean-wide tsunami (right). The yellow star is the earthquake epicenter. Units of the x-axis on the GPS seismograms (left) are minutes with respect to source time of the earthquake. SOURCE: Adapted from Blewitt et al., 2009.

measurements been available in 2004, the displacement of stations in Sumatra could have been measured with centimeter-level accuracy within minutes and thus could have indicated the true magnitude and tsunami potential of the Sumatra earthquake (Blewitt et al., 2006), thereby allowing for some warning.

OCEAN DYNAMICS

Geodesy, specifically satellite altimetry, in which a radar pulse is used to measure sea surface height, is critical to the study of ocean processes and their impacts on Earth's climate. Sea surface height measurements from the Topex/Poseidon and Jason-1 and Jason-2 missions are currently assimilated into global ocean circulation models to provide realistic information on the three-dimensional ocean circulation and state, as well as how those factors change over time (see Carton et al., 2008; Wunsch et al., 2007). Data assimilation (in particular the assimilation of altimetry data) into Ocean General Circulation Models is currently performed for operational oceanography, allowing ocean forecasting analogous to meteorological forecasting. In 1997–1998, the Topex/Poseidon satellite monitored an El Niño-Southern Oscillation (ENSO) event, offering the first space-based observation of such an event from its initialisation to its decay (see Fu and Le Traon, 2006). These observations helped clarify the role of equatorial waves in the movement of the warm pool, leading to significant revision of existing ENSO theories.

Satellite altimetry, which supplies continuous worldwide observations, also has considerably increased our knowledge of large-scale ocean circulation through mapping of the ocean surface topography (Fu and Chelton, 2001). Historically, geoid errors were the most limiting factor for precisely determining the ocean surface topography, and hence the large-scale surface circulation from which the deep circulation can be derived. The situation has considerably improved with precise geoid estimates based on the GRACE space gravimetry mission; further improvement is expected from the Gravity Field and Steady-State Ocean Circulation Explorer, launched by the European Space Agency in 2010. Among the most important discoveries from satellite altimetry is the strong mesoscale ocean variability observed almost everywhere in ocean basins, indicating that eddy energy generally exceeds the energy of the mean flow by an order of magnitude or more. Observations on this variability have provided new insights into eddy dynamics and the role of eddies in ocean circulation, heat, and salt transport (Fu and Ferrari, 2008).

Sea Level Change

One of the most important problems being monitored by satellite altimetry and tide gauges is the change in global and regional sea levels. Mean sea level rise has been observed by tide gauges for well over a century, but the global mean rate of sea level rise appears to be increasing over the more recent time periods. As shown in Figure 3.11, the observed global mean sea level rise was on the order of 1 millimeter per year from the late 19th century to the early 20th century, but then the rate appears to have doubled to 2 millimeters per year. During the past decade, this rate appears to have increased to approximately 3 millimeters per year. This significantly higher rate has been confirmed (see Figure. 3.12) by the series of ocean altimeter missions starting with TOPEX/Poseidon and continuing with Jason-1 and Jason-2 (Ablain et al., 2009; Beckley et al., 2007; Leuliette et al., 2004). In addition, regional sea level rise can be even more severe due to changes in large-scale ocean circulation patterns (see Yin et al., 2009).

A number of error sources have to be considered when interpreting the apparent global mean sea level rise, either from tide gauges or altimeter missions. For the tide gauges, the limitations are primarily the geographical distribution of the measurements (necessarily limited to coastal regions), and uncertainty in the vertical motions of the tide gauges themselves. With space-based altimeters, the

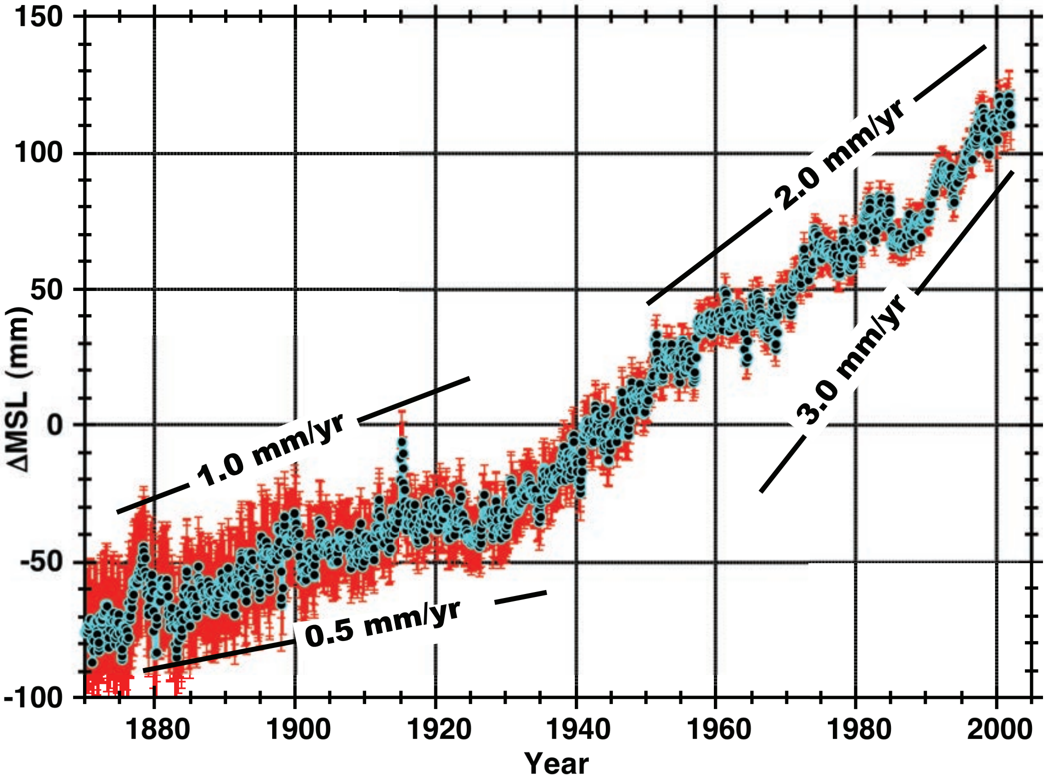


FIGURE 3.11 Sea level rise estimated from global tide gauge measurements. The average rate over the 1970–2010 period covered by the measurements has been approximately 1.7 mm/yr. However, the rate has clearly been accelerating over that period, as evidenced in the data by marked increases in slope. SOURCE: J.B. Minster, adapted from Church and White, 2006.

global ocean can be sampled much more uniformly, but a number of errors sources arise. Improvements to the global geodetic infrastructure will reduce these errors, improving our predictive capability.

Table 3.1 provides an estimate of the systematic errors in measuring the global mean sea level rise from altimeter data (adapted from Nerem, 2009). See also Ablain et al. (2009), where the details are slightly different but the net error is similar (approximately 0.4–0.6 millimeters per year). The altimeter drift error includes several components, predominantly the calibration of the microwave radiometers used for the wet troposphere correction. The reference frame errors can bias the results through drifts in the satellite orbits due to reference frame origin errors (see Beckley et al., 2007). For this particular error, there is considerable cancellation in the global value due to nearly equal and opposite contributions from the northern and southern hemispheres (they would cancel exactly if there was the same amount of ocean area in each hemisphere). Errors in regional sea level changes can be considerably larger than the global mean, exceeding one millimeter per year at the higher latitudes (Beckley et al., 2007). Since the slope of the shoreline amplifies the impact of the vertical change in apparent sea level, it is the regional sea level change that is critical for hazard assessment and mitigation. Another significant source of error is the altimeter calibration based on tide gauges that may have a common vertical rate error due to a reference frame scale error (Tapley and Ries, 2005). Unfortunately, for many tide gauges, there is no measurement of the vertical rate (whether uplifting, subsiding, or steady), and this also contributes to the uncertainty in the tide gauge calibration of the altimeter biases and drifts (Mitchum, 2000).

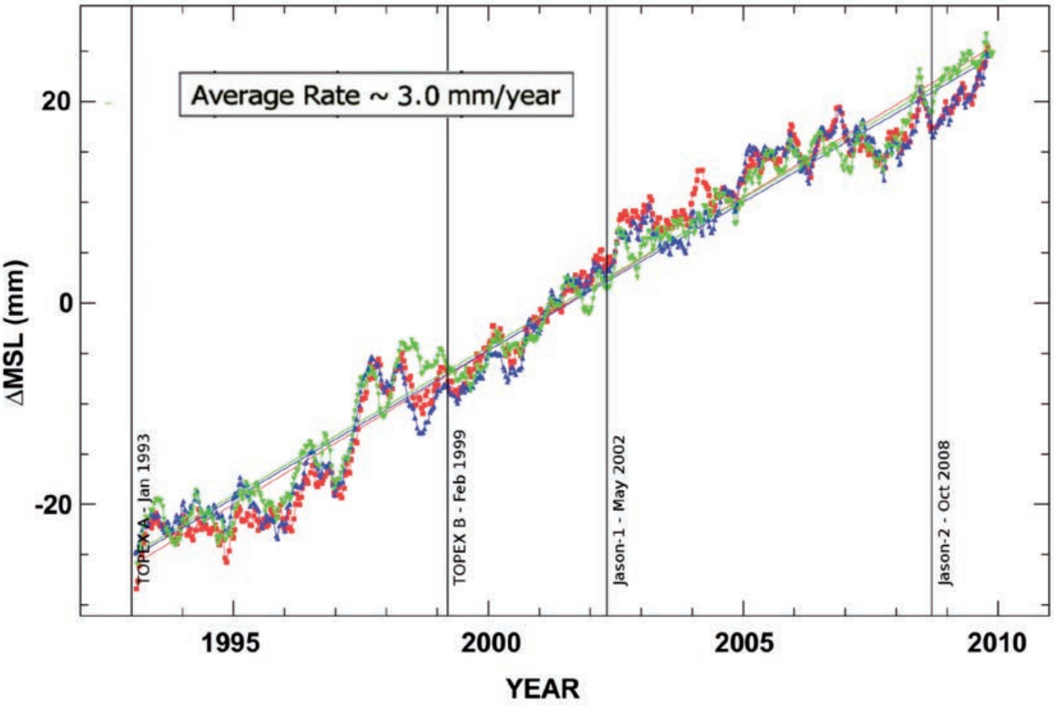


FIGURE 3.12 Three different determinations of sea level changes from the ocean altimeter missions TOPEX/Poseidon, Jason-1, and Jason-2 (M. Ablain, personal communication). The slope is the global mean sea level after correction for glacial isostatic adjustment. The vertical lines indicate important mission transitions; each represents a relative bias that must be determined through tide gauge calibration or through overlapping data analysis. Data from the University of Colorado (S. Nerem), blue curve; from the Goddard Space Flight Center/NASA (B. Beckley), red curve; and the Collecte Localisation Satellites-Laboratoire d'Etudes en Géophysique et Océanographie Spatiales (M. Ablain), green curve. SOURCE: Courtesy of M. Ablain, CLS, Collecte Localisation Satellites, Toulouse, France.

The uncertainty in estimates of global mean sea level can be compared to the two primary contributors to sea-level rise, thermal expansion, and ice melt. Over the altimetry time span (1993–2009), approximately one-third of the rise is attributed to the thermal expansion and two-thirds to melting of mountain glaciers and the polar ice sheets (Cazenave and Llovel, 2010; Leuliette and Miller, 2009; Nerem et al., 2006). The uncertainty from the reference frame and tide gauge vertical motion errors, up to 0.4 millimeters per year, is a considerable fraction of this mass loss estimate. The rate at which fresh water from ice melt is entering the oceans is a critical component of understanding what is causing the apparent acceleration of global mean sea level rise. There also is evidence that Greenland and Antarctica are losing ice mass at an accelerating rate (Chen et al., 2009; Jiang et al., 2010; Shum et al., 2008; Velicogna, 2009) and that the contribution to sea level rise from that loss will consequently increase further.

It is extremely important to identify and understand the sources of the current rise in global mean sea level, so that climate models can accurately reflect actual climate change processes. Consequently, precise geodetic measurements of the change in ocean volume (from radar altimetry), ocean temperature and salinity (from in situ instruments such as Argo), ice sheet mass balance (elevation change from radar and laser altimetry, coastal glacier flow from InSAR, and mass change from GRACE space gravimetry), and ocean mass (from space gravimetry) are all important pieces of the observational framework to test the validity of ice dynamic and ocean temperature change

TABLE 3.1 Estimate of Dominant Systematic Errors Sources in Measuring Global Mean Sea Level Rise from Space-based Altimeters

Altimeter Global Mean Sea Level Measurement Error Budget	
Glacial isostatic adjustment (affects volume of ocean basins)	0.1 mm/y
Altimeter drift error (predominantly radiometer drift)	0.4 mm/y
Altimeter bias errors (the ability to link overlapping missions)	0.4 mm/y
Reference frame origin error (affects the satellite orbits)	0.2 mm/y
Systematic vertical motion error (affects the altimeter calibration)	0.4 mm/y
Total error (root-sum-squared)	**0.6 mm/y**

models (see recommendations of the 2009 OCEANOBS workshop; Cazenave et al., 2010). All of the space-based techniques rely on an accurate reference frame, so maintaining and improving the accuracy of the terrestrial reference frame is of paramount importance for the study and for understanding global sea level rise. Ongoing research on altimeter drift and bias errors can be expected to reduce those uncertainties. The reference frame errors, however, are outside of the control of the altimeter data analysts and must be addressed by the geodetic community through improvements in the geodetic networks and the analysis of the data provided by those networks.

ICE DYNAMICS

One of the most dramatic effects of global change is the melting of ice from continental glaciers and polar ice sheets. Mountain glaciers around the globe have been in fast retreat for the past few decades, and observations indicate that the Greenland and Antarctic ice sheets are beginning to lose mass at alarming rates (Lemke et al., 2007). The acceleration of ice loss in Greenland and Antarctica was not widely anticipated before it was observed, and explanations to account for this acceleration are still incomplete. Only through careful monitoring of the ice sheets—using techniques that rely heavily on geodetic infrastructure—was the acceleration noticed and quantified. The continued application of current and future geodetic techniques is required for the scientific community to be able to monitor the ice sheet mass balance at the accuracy needed to understand what is happening today and to develop models for predicting future ice sheet mass changes. Of particular importance is the systematic application of geodetic imaging techniques that use radar and LiDAR to produce images of the Earth's surface wherein the location each pixel is known with geodetic precision, so that the difference between two pictures of the same area can be interpreted geologically and physically.

Information about the mass balance of the ice sheets is based on four types of remote sensing and ground techniques: (1) elevation change of the ice sheet, as measured by laser altimetry (for example, IceSAT), satellite radar altimetry (for example, ERS, EnviSat), and ground-based GNSS/GPS receivers; (2) measurements of horizontal velocities near the grounding line (where the ice starts to float free of its bed) of outlet glaciers using either on-ice GNSS/GPS receivers or satellite-based InSAR (for example, ERS, Radarsat, Envisat, ALOS satellites); (3) changes in the gravity field above the ice sheet, as measured by space-based gravimetry; and (4) geodetic measurements (for example, GNSS/GPS, gravity) of vertical motions in deglaciated areas. Monitoring changes in ice sheet elevation provides a direct estimate of changes in ice sheet volume, from which mass change is deduced based on the density through the snow/ice column. However, an accurate orbit is needed to achieve these calculations, which in turn depends on the accuracy of the reference frame. The GRACE mission (see Box 3.1) uses satellite-to-satellite tracking, as well as measurements from onboard GPS receivers and accelerometers, to determine global, monthly gravity solutions. These solutions can be used to map monthly changes in the distribution of mass at Earth's surface, and to determine the mass variability of Greenland, Antarctica, and major mountain glacier systems (for example, Alaskan coastal glaciers). The mass changes in Greenland from 2003 to 2008 are illustrated in Figure 3.13. The availability of data from a worldwide network of GNSS/GPS receivers is a critical component in the ability for GRACE to monitor these important mass changes.

To interpret space gravimetry and altimetry data over the ice sheets, it is necessary to correct for post-glacial rebound, also called glacial isostatic adjustment. This is corrected using models or by making direct GNSS/GPS measurements of the crustal motion on the ice-free land adjacent to the ice sheet. Each of these techniques involves geodetic instrumentation and relies critically on the geodetic infrastructure. Post-glacial rebound measurements by GNSS/GPS on ice-free land also require accurate reference frame determinations.

HYDROLOGIC CYCLE AND WATER RESOURCES

An overarching goal of observational hydrology is to better understand how water is transported and stored on and beneath the land surface. Traditional hydrological observations do not typically employ geodetic techniques, but with the advent of high-precision geodetic measurement systems, most of which depend heavily on the geodetic infrastructure, new and innovative methods for probing hydrological processes are providing valuable new information and hold great promise for the future.

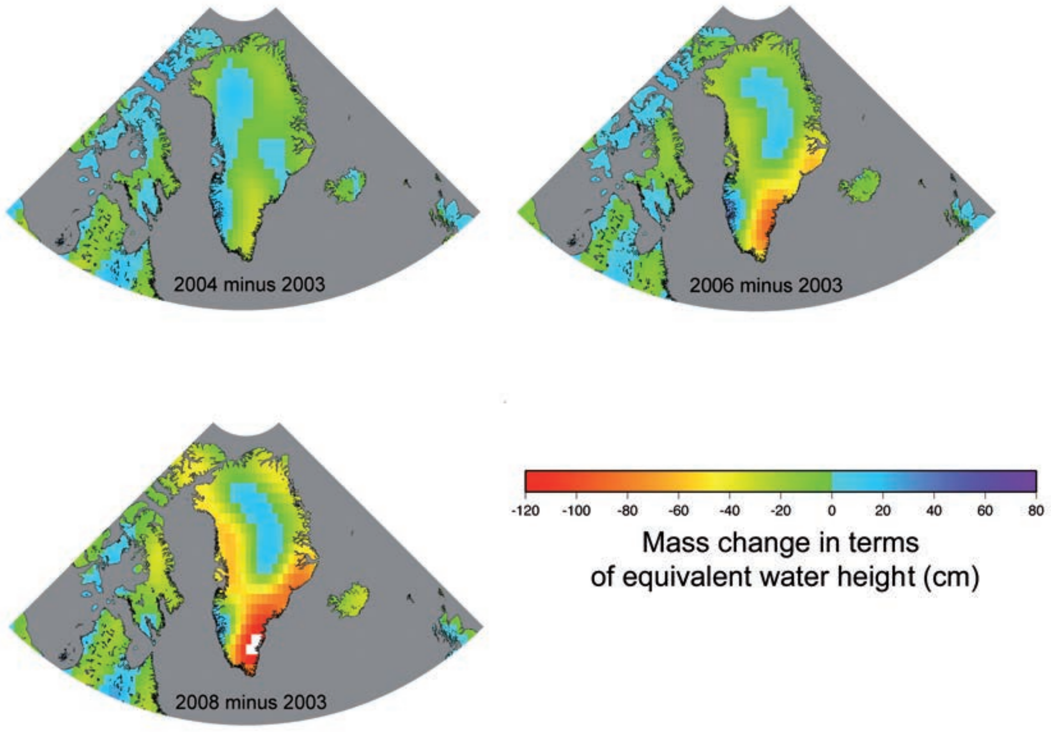


FIGURE 3.13 Mass changes in the Greenland ice sheets observed by GRACE. Observing the differences in the gravity fields determined in successive years reveals an ongoing loss of ice mass in Greenland, especially along the southeastern coast. There is evidence that the northwestern coast is now also losing mass. SOURCE: The University of Texas Center for Space Research.

Surface and Groundwater Storage

A change in water storage, on the surface or underground, involves a change in mass, which causes a corresponding change in the gravity field. The total change in water mass, therefore, can be estimated by measuring the change in gravity. These measurements can be made either from satellites or from surface gravity meters. The GRACE satellite mission, for example, is providing estimates of seasonal, yearly , and long-term changes in water storage at spatial scales of a few hundred kilometers and greater, to accuracies approaching one-centimeter water thickness, everywhere over Earth's surface. The results can be used to monitor the amount of water stored in underground aquifers (see Figure 3.14) and to assess and improve hydrological models. For example, the United States Drought Monitor and the North American Drought Monitor rely heavily on precipitation data and subjective reports. As GRACE data are combined with other observations and hydrology models, they will help improve these drought monitoring products and prediction tools. The GRACE results also will help to determine the role of continental water variability in global mean sea level change and to better understand the transfer of water between the land and the atmosphere (precipitation and evaporation) at regional scales (see Frappart et al., 2006; Rodell et al., 2007; Swenson and Milly, 2006; Swenson et al., 2006; Zaitchik et al., 2008). For shorter-scale information, surface gravimeters, which sit on Earth's surface and measure gravity changes directly at the instrument, are sensitive to changes in water storage averaged vertically through the ground directly beneath the meter (see Jacob et al., 2008; Van Camp et al., 2006).

Subsidence and Surface Displacement

In many cases, the vertical motion of the ground is caused by water storage changes. Various mechanisms can contribute to these changes. For example, when water storage decreases, the corresponding weight on Earth's surface decreases, and so the surface can rise. Alternatively, if water is drained from pore spaces underground, the pore spaces can contract, causing the overlying surface to drop (subside). A surface gravimeter will record a signal not only if there is an underlying change in mass, but also if the surface on which the meter sits goes up or down. In the latter case, gravity will change because the meter moves further or closer to Earth's center. This effect can confuse the interpretation of the results in terms of mass change, and so the vertical displacement of the surface is usually monitored independently, typically using GNSS/GPS receivers (van Dam et al., 2001). For example, local government agencies in Houston, in collaboration with the National Geodetic Survey, have established a network of permanent GPS receivers to monitor groundwater-related subsidence around the city (Zilkoski et al., 2001). Observations such as these not only provide indirect measurements of the aquifer drawdown but also help city planners understand and manage the possible effects of surface subsidence. GNSS/GPS results have even been used to estimate global-scale water storage by combining uplift measurements from globally distributed GNSS/GPS receivers (see Blewitt et al., 2001; Wu et al., 2003).

Groundwater-related surface motions also can be monitored using satellite or airborne InSAR measurements. Permanent GNSS/GPS stations provide continuous time-dependent displacements, but only at discrete points. In contrast, InSAR provides displacements over an entire region of tens of kilometers or more, though only at times when the satellite passes overhead (see Amelung et al., 1999; Buckley et al., 2003; Bawden et al., 2001). An example InSAR image of surface subsidence of New Orleans is shown in Figure 3.15. The subsidence is attributed to drainage projects that cause soil desiccation and oxidation, leading to compaction (Dixon et al., 2006). Data such as these provide information on the nature of the subsidence and on the possible hazards associated with that subsidence.

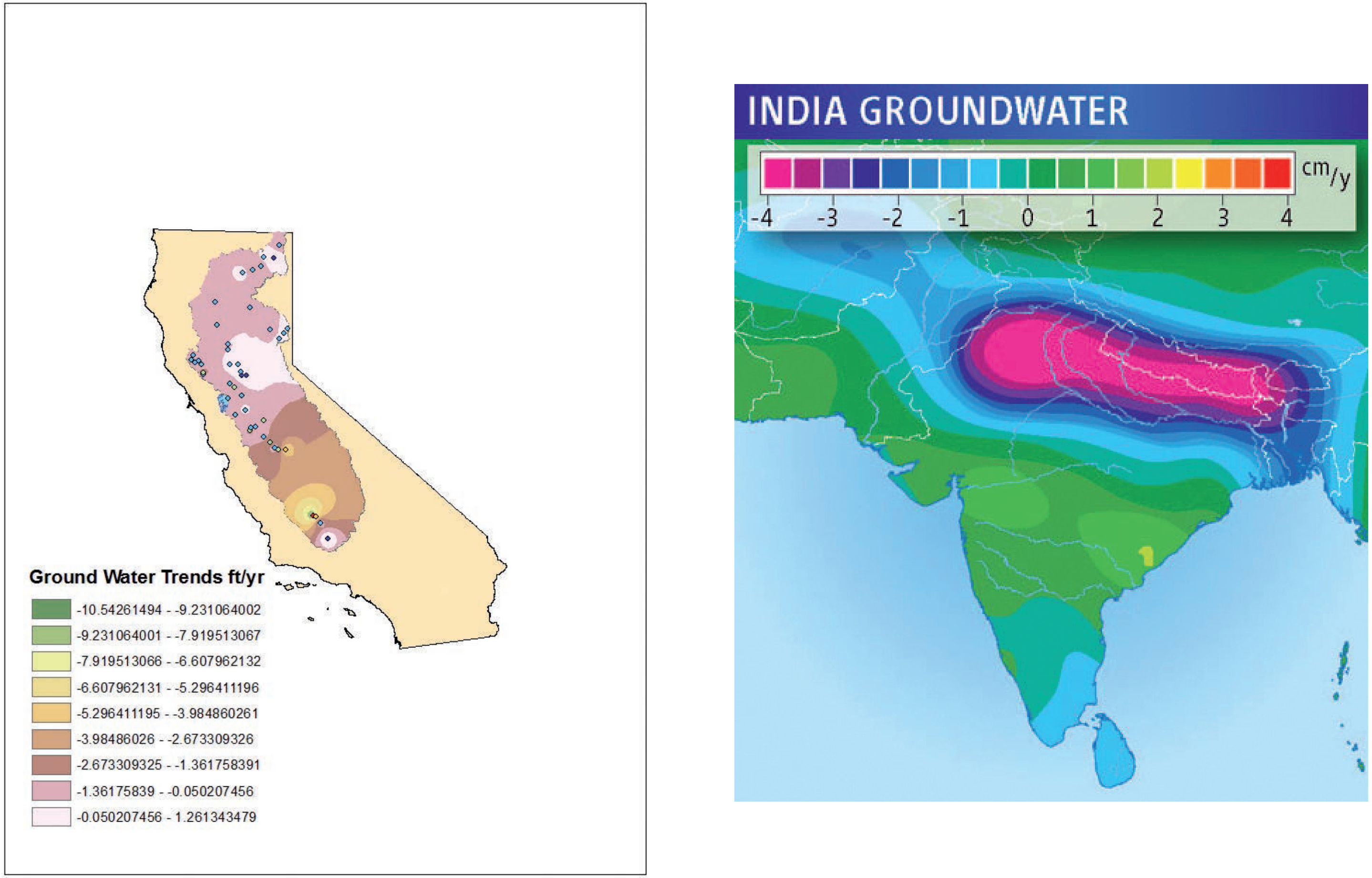


FIGURE 3.14 Major groundwater loss in the Sacramentro–San Joaquin River Basins in California (left) (Strassberg et al., 2009) and northern India (right) (Tiwari et al., 2009) revealed by the GRACE gravity mission and supplementary data. SOURCES: California groundwater iamge, NASA, http://www.nasa.gov/topics/earth/features/graceImg20091214.html (Left). India groundwater image, ScienceNOW, adapted from Tiwari et al., 2009 (Right).

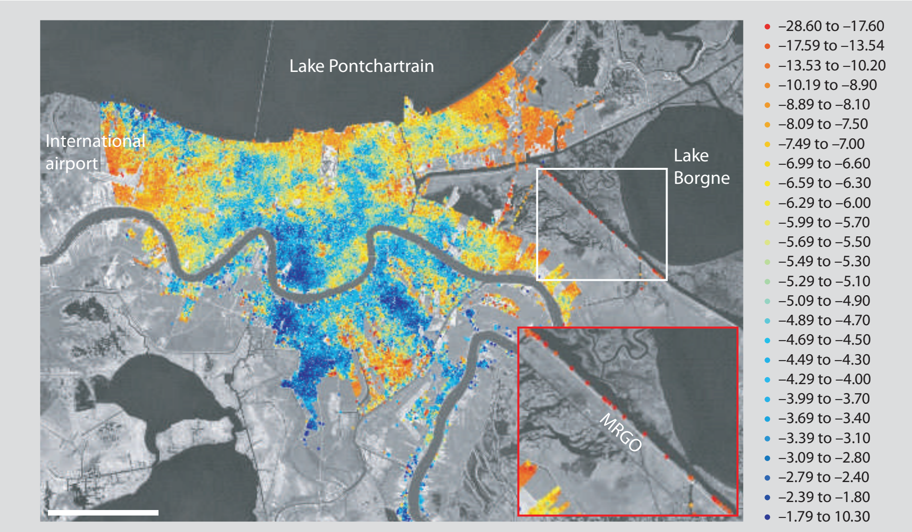


FIGURE 3.15 Map showing surface uplift rates (scale on right; units are millimeters per year) of New Orleans for 2002–2005, obtained from an InSAR analysis. Negative values for the uplift rates indicate subsidence. Most of New Orleans is subsiding relative to the global mean sea level, at an average rate of about 8 millimeters per year. Inset shows high subsidence rates between 2002 and 2005 on the MRGO levee, which later failed catastrophically during Hurricane Katrina. SOURCE: Dixon et al., 2006.

River and Lake Levels

In spite of the limitations of nadir-viewing radar altimetry (as opposed to side-looking radar imaging), monitoring surface water levels of rivers and lakes from space has a number of hydrological applications. These include studying the spatial and temporal effects of climate variability on surface waters, in particular over international river basins; improvement of models used in forecasts of hydrological variability; and water resource management (see Alsdorf and Lettenmaier, 2003; Cretaux and Birkett, 2006; Calmant and Seyler, 2006). Over floodplains, the combination of altimetry-based water levels with radar or visible satellite imagery allows scientists to monitor changes in surface water volume, particularly during floods (see Frappart et al., 2006). Laser altimetry (for example, the Ice, Cloud, and Land Elevation Satellite, or ICESat, mission) is also being used. More than 15 years of radar altimetry measurements are now available for several thousand continental lakes, as well as for "virtual stations" on rivers (the intersection of the satellite ground track and the river) and floodplains. Typical height precision over lakes, where data from several altimetry missions can be combined, is a few centimeters. Over rivers, altimetry-based height precision is less accurate (in the range of 10–40 centimeters) for two reasons: (1) only those data that come from repeat passes over the same satellite track can be combined in a single analysis, so there is limited data available except along very large rivers, and (2) because of the large radar footprint, reflections from river banks perturb radar echoes (waveforms); moreover, unlike for oceans, there is no simple interpretation of river waveforms.

A new concept of wide-swath radar interferometry has been recently proposed (Alsdorf et al., 2007) to monitor surface waters with unprecedented resolution (of approximately 100 square meters) and provide global coverage of worldwide rivers, lakes, and floodplains every few days. This mission, called SWOT (Surface Water Ocean Topography), was recommended by the NRC "Decadal Survey" and is listed among NASA's future priority missions. SWOT will open a new era in land hydrology, offering important new perspectives for studies on the terrestrial water cycle, flood prediction, and water resources.

WEATHER

Satellite imagery shown on television can give the impression that weather forecasts are based on these images, but forecasts actually come from physics-based models of the *troposphere*, the lowest 14 kilometers of the atmosphere. These models must continuously ingest measurements of the atmospheric state (pressure, temperature, humidity, and winds) at different altitudes around the planet to stay aligned with actual atmospheric conditions. The ability to predict both the severity and the temporal and spatial extent of weather changes, especially precipitation, is critical for public safety and agriculture, and governments around the world collaborate to collect the data used in forecasts. For decades, the input data for these models were provided by radiosondes, better known as weather balloons. Unfortunately, the spatial distribution of radiosonde sites is limited both by lack of coverage over oceans and by a significantly reduced number of sites in the southern hemisphere. Increasing the number of radiosonde launches per day is constrained by the cost of the instrumentation, which cannot be reused. Geodesists focused on precise positioning use corrections to remove atmospheric effects, which are considered to be a source of noise in their measurements. Conversely, these same corrections may be used by meteorologists to better understand the atmosphere. Thus, improvements in the geodetic infrastructure benefit both fields of science.

Ground-based Measurements

Atmospheric refraction effects have long been recognized as an important error source in geodesy. Instead of relying upon uncertain models, space geodetic techniques such as GNSS/GPS estimate tropospheric variations along with the positioning parameters of interest. Eventually, it became possible to reverse the problem; assuming that the station position is well-determined, scientists could use the “nuisance” signal in the GNSS/GPS estimates to recover the time-varying behavior of the atmosphere (Ware et al., 2000). Unlike radiosondes, which measure the atmosphere conditions at multiple altitudes, ground-based GNSS/GPS measures only the “integrated” effect of the atmosphere, that is, how much the atmosphere delays the measurement in total. About 80 percent of the delay (known as the “dry troposphere”) can be predicted if surface pressure is measured. Once the dry troposphere delay is removed, one can recover the delay due to water vapor, which can be scaled to what is called precipitable water vapor (PWV). Measurements of PWV estimate moisture and latent heat transport models, which are critical for weather forecasts. To be useful for weather forecasting, however, the data must be available at close to real time.

Since PWV varies both in space and time, globally distributed and frequently collected data are needed. For the current constellation of approximately 30 satellites, a single GNSS/GPS receiver will typically receive signals from 6 to 12 satellites. These data are primarily used to estimate PWV in the column of air above the GNSS/GPS receiver. But, in principle, having measurements from more than one direction means that GNSS/GPS has azimuthal, as well as vertical, sensitivity. The more satellites that are transmitting signals from a given direction, the greater the sensitivity will be. This also means that the combination of signals from multiple systems, such as Galileo, GLONASS, and COMPASS, will yield even more sensitive atmospheric monitoring capabilities than are achievable from the United States’ GPS alone. In addition, because GNSS/GPS receivers operate continuously, GNSS/GPS atmospheric sensing has extraordinary temporal sensitivity, which is particularly important for monitoring and predicting the behavior of strong weather events.

Because the atmospheric delay is intrinsically related to how well position can be determined, GNSS/GPS tropospheric studies require the same infrastructure: accurate orbit determination, along with a stable reference frame. Atmospheric applications require a co-located barometer to allow removal of the pressure, or "dry troposphere," effect. Well-designed sites with low multipath errors are also valuable as they will produce more accurate estimates of PWV. For weather prediction, however, there is the additional requirement that accurate orbits must be available in real time, whereas for climate studies, orbits can be made available in days to weeks. In order to achieve real-time accuracy, a reliable, globally distributed network of at least 50 real-time GNSS/GPS sites must be maintained. Rapid analysis of the data produced by this tracking network also must be supported (see Chapter 4). In order to improve the value of the large number of existing GPS receivers in the United States for meteorology, real-time telemetry capabilities would need to be expanded.

Space-based Measurements

While GNSS/GPS receivers have much greater temporal sensitivity than radiosondes launched twice per day, GNSS/GPS receivers have similar spatial limitations, in that they are (currently) limited to land and are present mostly in the northern hemisphere. For this reason, the atmospheric science community has actively sought measurements with better spatial density in the southern hemisphere and over the oceans. In the early 1990s, it was proposed that limb-sounding, a method that had been used to sense planetary atmospheres, could provide spatially dense measurements of Earth's atmosphere. In a limb-sounding, or radio occultation, experiment, a radio signal is tracked from space rather than from Earth (Figure 3.16). This means that the horizon restriction is eliminated, and the signal can be refracted through the atmosphere for very long distances. The more GNSS/GPS and low-Earth orbit satellites are available, the more occultations that can be retrieved per day.

After the success of a proof-of-concept satellite mission in the late 1990s (Kursinski et al., 1996), the six-satellite Constellation Observing System for Meteorology Ionosphere and Climate

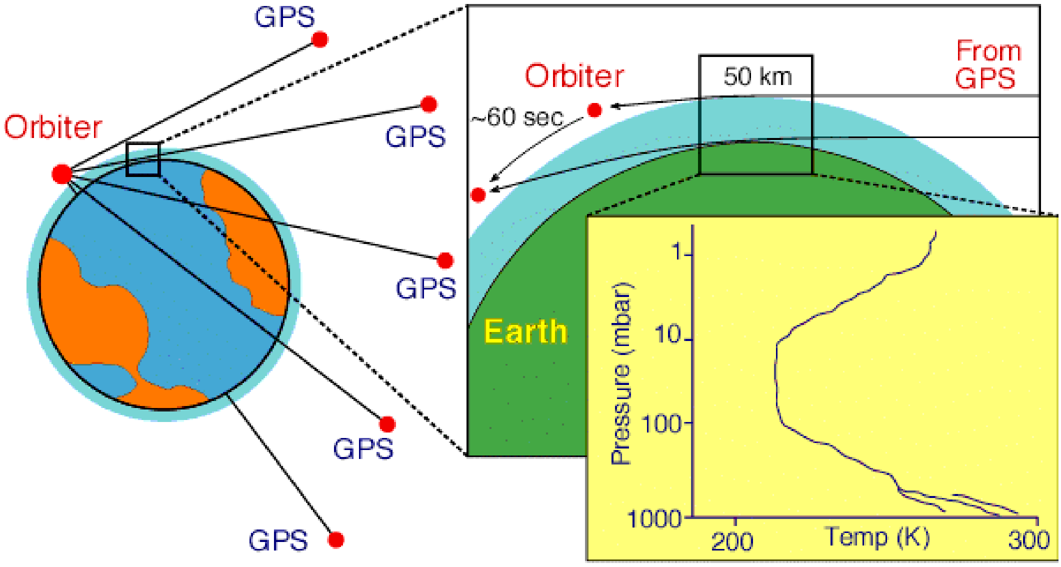


FIGURE 3.16 Schematic of a GNSS/GPS radio occultation, or limb-sounding, measurement. Signals transmitted by a GNSS/GPS satellite are refracted by the atmosphere and received by the orbiter, generating a vertical profile of pressure and temperature through the atmosphere until the signal is eventually blocked (occulted) by Earth. SOURCE: Yunck, 2002.

(COSMIC) was launched in 2006. Now operational, COSMIC provides global three-dimensional coverage of atmospheric temperature and water vapor from Earth's surface to 40 kilometers (Anthes et al., 2008). In one day, COSMIC produces more than 1,000 well-distributed "soundings" in the southern hemisphere, compared to just over 100 southern hemisphere radiosondes above the continents. Furthermore, COSMIC is an all-weather system, and thus provides crucial data from the polar regions, observations for which are currently limited by weather restrictions. These new GNSS/GPS occultation data reduce uncertainties in both global and regional weather analysis and are routinely assimilated into both U.S. and European weather forecast models. In order to operate properly, however, they have requirements similar to those of ground-based GNSS/GPS networks, including accurate orbits and reference frame (which require a global GNSS/GPS tracking network providing near-real-time data). In addition, the velocity of the GNSS/GPS satellite relative to the low-Earth orbit satellite must be known to 0.1 millimeters per second, placing stringent demands on near-real-time orbit determination precision.

SPACE WEATHER

Above altitudes of 70–400 kilometers, the atmosphere is so thin that free electrons can exist. This ionized portion of the atmosphere contains a plasma—the ionosphere—in which the magnitude of the ionization is controlled by solar activity. Characterizing changes in the ionosphere is important, because these changes—known as "space weather"—can have severe adverse effects on the increasingly sophisticated ground- and space-based geodetic systems of importance to governments, corporations, and citizens. As described by Buonsanto (1999), the effects of space weather include "electric power brownouts and blackouts due to damaging currents induced in electric power grids, damage to satellites cause[d] by high energy particles, increased risk of radiation exposure by humans in space and in high-altitude aircraft, changes in atmospheric drag on satellites, errors in GPS and in VLF (Very Low Frequency) navigation systems, loss of HF (High Frequency) communications, and disruption of UHF (Ultra High Frequency) satellite links due to scintillations."

Before the advent of ground-based GNSS/GPS, researchers relied on limited and expensive in situ observations of the ionosphere. After the first GNSS/GPS satellites were launched, it was recognized that GNSS/GPS could be used to monitor ionosphere variations (see Coster and Komjathy, 2008). The effect of the ionosphere on a radiometric signal is a time delay in the signal that is proportional to the level of ionization, described by the total electron content (TEC), along the signal path. The delay is also proportional to the radio frequency being used, so ionospheric scientists use the fact that the L1 signal (1575.42 MHz) has a different delay than the L2 (1227.60 MHz) to produce global maps of TEC. Currently, these maps include GNSS/GPS measurements from more than 1,000 receivers (Komjathy et al., 2005). The NOAA Space Weather Prediction Center assimilates GPS data to model TEC over the United States (Fuller-Rowell, 2005). Figure 3.17 is an example of the TEC distribution over the United States during a period of relatively low solar activity.

Global maps of TEC distribution are produced by the International GNSS Service and NASA JPL. However, ground-based TEC studies are intrinsically limited by the lack of GNSS/GPS receivers in the southern hemisphere and over the oceans. Missions such as COSMIC can produce 1,000–2,500 TEC profiles through the ionosphere, enabling a more accurate three-dimensional image of the ionosphere (see Anthes et al., 2008).

Ionosphere maps can be used to calibrate single-frequency systems that are commonly used by surveyors, which cannot remove the ionosphere effect by themselves. They also can be used to study the temporal and spatial behavior of ionospheric TEC. Using GNSS/GPS for ionosphere mapping requires additional information that is typically not needed for positioning or troposphere studies. The hardware delays for the two signals on each GNSS/GPS satellite must be known very precisely, as well as hardware biases within the GNSS/GPS receivers. Because the estimation of

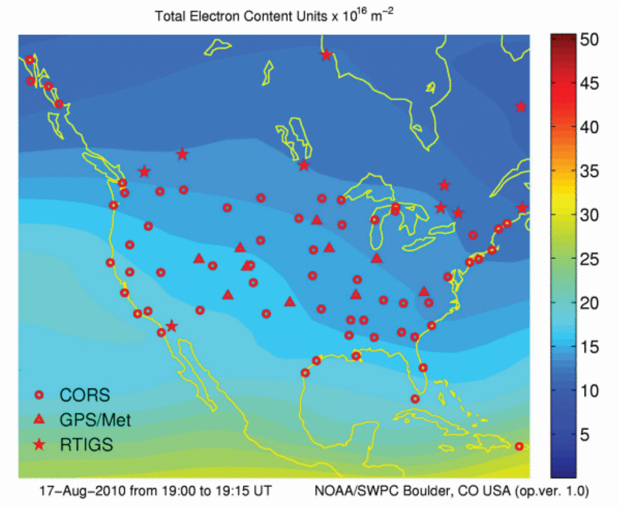


FIGURE 3.17 Example of an ionosphere map produced by the NOAA Space Weather Prediction Center August 17, 2010. The unit for total electron content (TEC) is 10^{16} electrons per square meter (the total number of electrons in a tube with a cross-section area of one square meter, extending vertically from the surface through the ionosphere). SOURCE: NOAA, http://www.swpc.noaa.gov/ustec/.

these biases is far more difficult in the presence of multipath error, the best way to improve knowledge of instrumental delays would be to improve multipath conditions at GNSS/GPS sites. This requires coordination on the national level to define the site requirements for infrastructure and to establish the leadership structures for implementing these requirements. The space weather community also would benefit from more sites that telemeter data in real or near-real time. The NOAA Space Weather Forecasting network now uses data from only approximately 100 real-time sites. These sites can easily assimilate more data. The United States now has more than 2,000 GPS sites supported by a variety of government agencies; however, data from these sites are often transmitted only once per day.

The Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) system also can contribute to monitoring space weather through the launch of specially designed instruments that take advantage of worldwide DORIS transmitting beacons. The primary objective of the Scintillation and Tomography Receiver in Space (CITRIS) is to detect ionospheric irregularities from space at low latitudes. CITRIS, developed at the U.S. Naval Research Laboratory, differs from the normal DORIS receiver in that it is able to capture two-frequency transmissions at a sample rate of 200 hertz. With CITRIS flying on the U.S. Space Test Program satellite STPSat-1, two years of data were collected and processed to determine the fluctuations in ionospheric TEC and radio scintillations associated with equatorial irregularities (Bernhardt and Siefring, 2010).

PRECISION SPACECRAFT NAVIGATION

Precision Orbit Determination for Near-Earth Satellites

Over the past several decades, the requirements for highly accurate determination of the orbits of near-Earth satellites have been driven by the evolution of the fields of satellite geodesy, including reference frame and gravity field determination, satellite radar and laser altimetry, and InSAR. The ability to use accurate range and range-rate measurements between an orbiting satellite and tracking systems located on Earth's surface has provided a dramatic improvement in the ability to monitor tectonic deformation and subsidence as well as monitor small but important changes in Earth's rotation. The ability to use satellite altimeter measurements to obtain accurate, globally distributed observations of the ocean surface has opened a new era in oceanography. These same tracking measurements, along with satellite-to-satellite measurements, are providing unparalleled views of Earth's gravity field and the gravity signals associated with temporal variations in the distribution of mass within Earth. These advances are intimately tied to the advances in precision orbit determination of Earth-orbiting satellites.

Determining the orbit of near-Earth satellites involves four elements: (1) equations describing the motion of the satellite; (2) a numerical integration procedure for the equations of motion; (3) accurate observations of the satellite from the ground or other satellites; and (4) an estimation method combining the results of the first three elements to estimate the satellite's position (Tapley and Ries, 2003). Continuous measurements of the three-dimensional position of a spacecraft are usually not available, but as long as the observations depend on the satellite's motion, they contain information that helps to determine the orbit. The evolution of the satellite's position and velocity must be consistent with both the physics of the mathematical model and the sequence of observations, which constrains the estimated orbit to a specific solution. As the tracking data and mathematical models for satellite dynamics have steadily improved, the accuracy of orbit determination also has improved. For example, whereas typical orbit accuracy for geodetic satellites was at the several-meter level in the 1970s, centimeter-level orbit accuracy is now achievable when high-precision tracking systems (GNSS/GPS, SLR, and/or DORIS) are used. This accuracy has been enhanced by the availability of dramatically improved Earth gravity models provided by the GRACE mission.

Interplanetary Navigation

The primary aim of interplanetary spacecraft navigation is to position spacecraft relative to solar system bodies for precise fly-bys, orbit insertion, and surface landings. This differs significantly from near-Earth orbit determination because of the difficulty in obtaining tracking, the geometry of that tracking, and the long delays in receiving signals from distant spacecraft. The data used in interplanetary spacecraft tracking are generally radiometric measurements of range, range-rate, or the interferometric difference of signal arrival times, which are provided by very large radio antennas such as those of the Deep Space Network. Optical (image) measurements also have been used, but, in recent years, these are most often performed with the imaging systems on the spacecraft as opposed to terrestrial optical telescope measurements. Interplanetary laser ranging, using transponders or one-way systems, are already being investigated, such as the current tests of one-way laser ranging to the Lunar Reconnaissance Orbit.

Like near-Earth orbit determination, the basic analysis of spacecraft-tracking data requires relating the position of the spacecraft to the position of the tracking system, but rather than orbiting Earth, an interplanetary spacecraft is orbiting the sun or some other planet. The geometry of the basic measurement of range or range-rate is not sufficient to directly determine a spacecraft's position, but the equations of motion for the spacecraft are very accurately known. Combined with precise knowledge of the tracking station's position, a sufficient accumulation of tracking data constrains the possible motions of the spacecraft to a particular trajectory. For this, accurate coordinates as a function of time (ephemerides) for the solar system bodies also are needed. To keep improving the planetary ephemerides, tracking data collected on spacecraft near planets are incorporated with radar and optical measurements of the planets (Standish, 1998). Another important requirement is knowledge of Earth's orientation in space, particularly Earth's rotation angle (denoted as Universal Time 1, or UT1, a nomenclature leftover from when time was determined by Earth's rotation rather than atomic clocks). Wind and water movements on Earth cause UT1 variations and cannot be predicted into the future with high accuracy. Determining Earth's orientation with real-time accuracy would require a station position equivalent of 30 centimeters, which, for UT1, requires accuracies of 650 microseconds. Current spacecraft navigation systems obtain 24-hour prediction accuracies, or 125 microseconds for UT1.

TIMING AND TIME TRANSFER

The high-accuracy timing methods at the heart of geodetic techniques are useful for precise measurements of time and frequency. The ability to synchronize distant clocks accurately is an operation commonly referred to as "time transfer." Time synchronization requirements for such everyday functions as bank transfers, transportation, television broadcasting, and power grid regulation are on the order of milliseconds or less. GNSS/GPS signals are the most popular and economical way to achieve clock synchronization for most of these commercial applications. Scientific applications have yet more demanding time synchronization requirements, at the nanosecond level (10^{-9} seconds) or better. "Precise time-transfer" is typically only needed to synchronize clocks with comparable precisions (for example, atomic clocks). Because no single clock can be expected to be absolutely stable or reliable, the international definition of time for Earth (International Atomic Time or TAI) is based on an ensemble of approximately 300 atomic clocks in various laboratories around the world. Since these clocks must be compared constantly to produce the official time system, the precision of the time-transfer method is just as important as building the clocks themselves (Arias, 2005). The United States has demonstrated its long-standing commitment to the definition of TAI by contributing more than half of the clocks used to define the international timescale.

Before the advent of GNSS/GPS, the most precise method for time-transfer was TWSTFT—two-way satellite time and frequency transfer. TWSTFT used laboratory-based transponders and expensive commercial satellites with a precision of approximately 0.5–1.0 nanoseconds (Hanson, 1989). With GNSS/GPS now freely available, methods developed by the geodetic community have improved precision by a factor of 10 (Bauch et al., 2006; Larson et al., 2000). Meanwhile, kilohertz time transfer is being tested on the Jason-2 mission with the T2L2 experiment, where picosecond-level stability over several minutes may be achievable. In addition to the international timescale TAI, a few countries operate their own primary frequency standards (Arias, 2005). NIST-F1, a cesium fountain frequency standard operated by the National Institute of Standards and Technology, serves as the United States' primary frequency standard, with an uncertainty of 5×10^{-16} (such a clock does not lose or gain more than one second in 60 million years). Such extraordinarily accurate clocks place the most demanding requirements for time transfer capabilities on the geodetic community and infrastructure.

DECADAL MISSIONS

The NRC's *Earth Science and Applications From Space: National Imperatives for the Next Decade and Beyond* (known as the "Decadal Survey," NRC, 2007a) recommended a number of efforts and missions to address a wide range of scientific and societal challenges, from scientific questions related to melting ice sheets and sea level change to the occurrence of extreme events like earthquakes and volcanic eruptions. Specifically, the Decadal Survey recommended three space geodetic missions: ICESat-2, DESDynI, and GRACE-II. **The committee agrees with these recommendations as being of high priority to the nation. Moreover, there is an important synergy between these missions and the current geodetic infrastructure that increases the potential for scientific discovery and other societal benefits associated with these Decadal Survey missions.**

As noted in the Decadal Survey, sea level will change in part due to the thermal expansion (or decrease in water density) of the oceans as a result of a global-scale increase in temperature combined with the addition of water volume from melting mountain glaciers and ice sheets. Of these factors, changes in the volume of ice sheets in response to climate change is the least understood. The laser altimeter on ICESat-2 would quantify polar ice sheet contributions to recent sea level change and illuminate the linkages to climate conditions. It also would quantify regional signatures of ice sheet changes to assess the sources of that change and to improve predictive models, as well as estimate sea ice thickness to examine how ice, the ocean, and the atmosphere exchange energy, mass, and moisture. Massive urbanization and the extensive societal and economic infrastructure that has developed in coastal areas over the past century make the precise monitoring of sea level critical. In addition, ICESat-2 would measure vegetation canopy height as a basis for estimating large-scale land biomass (the amount of living matter in a given area) and biomass changes. Land biomass stores a significant amount of carbon. Measurement of canopy height will allow scientists to better assess the effects of climate and land management on vegetation and to improve understanding of the global carbon budget.

The DESDynI (Deformation, Ecosystem Structure and Dynamics of Ice) mission would employ an L-band Synthetic Aperture Radar (SAR) and multiple-beam LiDAR to monitor surface deformation and terrestrial biomass structure. Observing surface changes is critical for estimating the likelihood of earthquakes, volcanic eruptions, and landslides, and for predicting the response of ice masses to climate change and the impact of that response on sea level. Monitoring the size and distribution of vegetation will enable characterization of the effects of changing climate and land use on species' habitats and the global carbon budget.

The GRACE-II gravity monitoring mission, which proposes to use lasers instead of microwaves for satellite-to-satellite tracking, is expected to provide hydrological measurements down to scales approaching 100 kilometers or better (see Box 3.1). However, to avoid an undesirable gap in the gravity monitoring missions between GRACE and GRACE-II (proposed for the 2016–2020 time frame), a GRACE follow-on mission is now planned. These measurements will allow scientists to track large-scale water movement over the entire globe in order to better understand Earth's hydrological cycle, provide inputs to meteorological models, detect changes in aquifers for improved groundwater management, and assess changes in ice sheet volume and distribution to improve predictions of sea level change.

These Decadal Survey missions are highly complementary and are essential to fully exploiting existing geodetic observation systems. For example, uncertainty in the models for how Earth's crust accommodates changing ice load (post-glacial rebound or glacial isostatic adjustment, GIA) currently hampers the determination of changes in the Antarctic and Greenland mass balance using satellite gravity measurements. However, by combining satellite gravity measurements with satellite altimetry, it is possible to distinguish between GIA and ice mass change, because GIA-induced changes (which involve relatively dense rock) will produce a different combination of surface and gravity change than those produced by variations in ice alone. Over vegetative areas, the laser altimeter and microwave SAR instruments will monitor surface deformation at different frequencies to more precisely separate biomass changes from surface topography changes. Between the three missions, changes in mass and surface topography for nearly all of Earth's land area will monitored for seasonal and long-term changes.

SUMMARY

The operational applications and scientific research made possible by an accurate and easily-accessible global geodetic infrastructure are limited only by the imagination of the user community. The examples presented in this chapter were selected to provide some sense of the variety of applications in various stages of development and routine use. As the extent, density, accuracy, and accessibility of the geodetic infrastructure continues to improve, the scientific applications will continue to grow, enabling new services to be developed and new challenges to be solved.

In addition to existing systems, some "Decadal Survey" missions—DesDynI, GRACE-II, and ICESat-II—also have the potential for great direct public benefit. They will each measure, in real time, an important component of the climate system. This not only will enable scientists to gather valuable data about climate, but also will provide the public with images that will enable them to visualize the dynamic Earth system and to understand the connection and interaction among the global water cycle, climate, and the solid Earth. The Decadal Survey missions also will benefit greatly from the global geodetic infrastructure. Indeed, these missions have the potential to become part of the infrastructure by providing unique geodetic information.

4

The Geodetic Infrastructure: Current Status and Future Requirements

The geodetic infrastructure consists of two principal components: (1) the network of observation instruments for each geodetic observation technique; and (2) associated international services composed of the various scientists, technicians, and administrators that support each technique. This chapter describes the current status of the main geodetic networks, the Earth observation satellites that underpin those networks, and the international services that support them as well as future technological and organizational needs in each of these areas.

GEODETIC NETWORKS

Very Long Baseline Interferometry (VLBI)

VLBI is a geometric technique that employs radio telescopes located thousands of kilometers apart to observe natural radio sources that are located billions of light-years from the Earth, such as quasars (see Figure 4.1). Although the observations from these telescopes are useful for radio astronomy, they also have important applications for geodesy. Because the radio sources are at such extreme distances they appear fixed in space and provide the most stable celestial reference frame (the reference frame that does not rotate relative to distant stars and is centered at the Solar system's center of mass) that currently can be defined. As a result, VLBI is the definitive technique for tracking changes in the orientation of Earth in space, including precession, nutation, Earth rotation and, when VLBI is combined with Global Navigation Satellite Systems/Global Positioning System (GNSS/GPS) measurements, polar motion. The VLBI infrastructure includes the radio telescopes ("VLBI observatories") and central data processing facilities called correlator centers. Each technique also has an associated international service that is a critical component of the infrastructure; these services are discussed later.

The International VLBI Service is an international collaboration of organizations that operate or support VLBI infrastructure (Schlüter and Behrend, 2007). Figure 5.1 illustrates the geographical distribution of the VLBI observatories that contributed geodetic data during 2008. The antennas in Fortaleza, Brazil and Hartebeesthoek, South Africa are currently inoperative but repair plans are

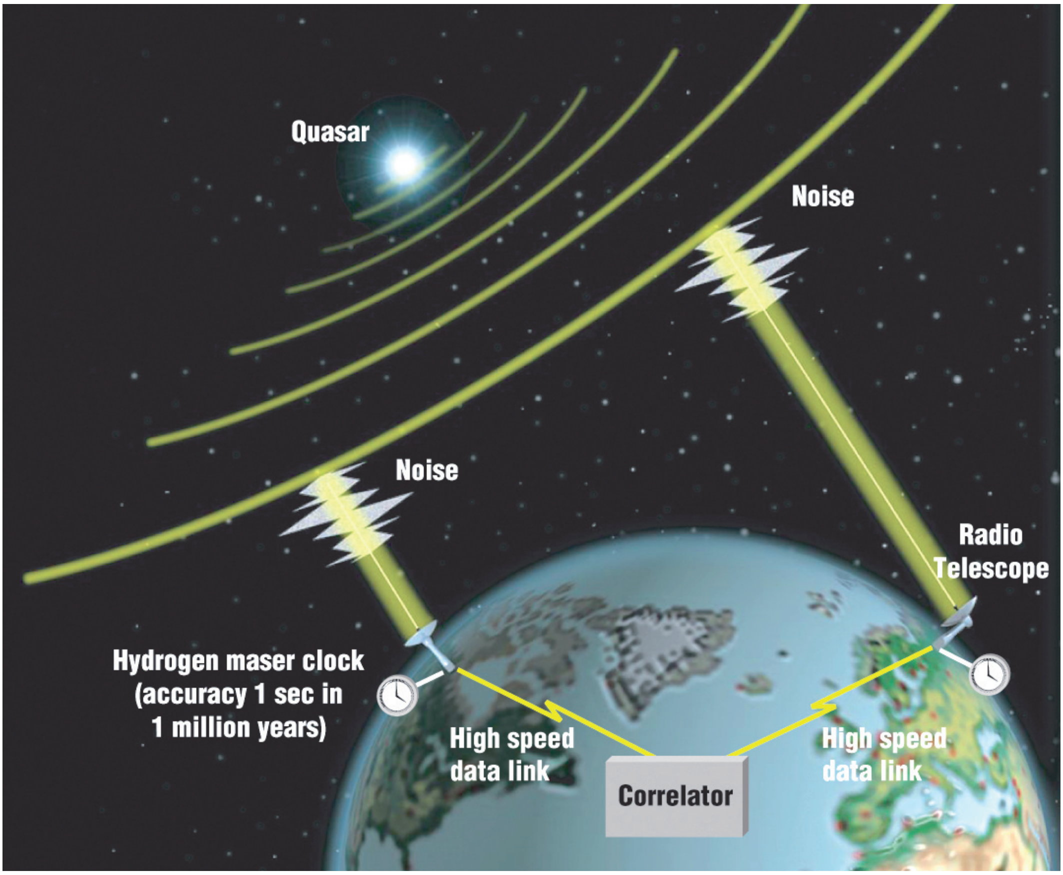


FIGURE 4.1 The VLBI technique uses multiple radio telescopes to measure natural radiometric noise from distant radio sources, such as quasars. The differences in the arrival time for the same radio noise at separate antennas are later correlated to determine the time delay between the two antennas to millimeter precision. By observing radio sources in multiple directions, the VLBI network can be used to determine Earth's geometric shape and orientation in space. SOURCE: NASA, Goddard Space Flight Center.

in place. The two Canadian VLBI stations at Yellowknife and Algonquin have been shut down. The U.S. VLBI site in Gilmore Creek, Alaska was closed by NASA, and the geodetic VLBI site at Green Bank, West Virginia (originally part of the U.S. Naval Observatory program for Earth orientation) closed in 2001. There are currently no prospects for restoring either of the closed U.S. sites. Furthermore, those U.S. sites that are operational are not all operating routinely. Except for the sites at Kokee Park, Hawaii and Westford, Massachusetts, most U.S. VLBI sites collected less than ten days of data during 2009. If four non-colinear U.S. sites were routinely operational for geodetic observations, this would be sufficient for USNO to determine Earth's orientation using U.S. resources only. Currently, USNO has to rely on international partners for its Earth orientation determination.

Several factors make the VLBI technique challenging and costly. First, the requirement that data from VLBI observatories must be physically shipped to a special correlator center for processing can introduce delays in determining Earth-orientation parameters. The signals from quasars far from Earth are weak and it is necessary to process the data from VLBI observatories centrally in order to separate the signals from background noise. In addition, obtaining usable signal-to-noise levels using

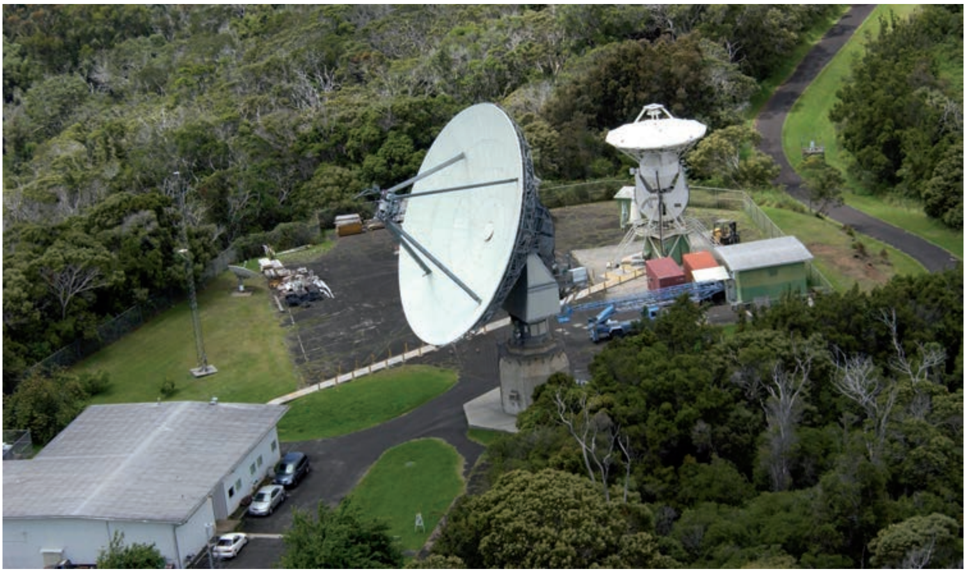


FIGURE 4.2 The 20-meter antenna at the Kokee Park Geophysical Observatory, NASA's VLBI station in Hawaii, is one of the most active sites in the global VLBI network. SOURCE: U.S. Navy Pacific Missile Range Facility.

VLBI requires large directional antennas (see Figure 4.2) that are able to move rapidly to obtain the required geometrical distribution of observations. This requirement makes VLBI instruments technologically complex and costly, and it is difficult to determine the location of the antenna's reference point at the desired one-millimeter-level for such large antennas (see Chapter 5).

The requirements outlined in the Global Geodetic Observing System project of the International Association of Geodesy, combined with the science goals specified in the NASA Solid Earth Science Working Group Report, establish three main criteria for the next generation of geodetic VLBI systems (VLBI2010) (Niell et al., 2006). These include one millimeter measurement accuracy, continuous measurements for station positions and Earth orientation, and a turnaround time of less than 24 hours.

Recommendation: To pursue these system enhancements, the United States should invest in the following future developments to make VLBI more effective and less expensive:

(1) **Radio telescope apertures should be reduced (to 10-12 meters) by increasing the recorded signal bandwidth.** The benefits of smaller telescope apertures include: lower manufacturing and maintenance cost; higher attainable slew rates; lower instrument distortions associated with temperature changes and gravitational and wind loading; increased ease of locating the effective reference point; and reduced cost of piers and domes at observing stations. The optimal radio telescope parameters for geodetic applications are different than those for astronomical applications. The geodetic infrastructure must, therefore, include a dedicated network of geodetic VLBI observatories to obtain continuous measurements. In addition, using multiple VLBI antennas at some locations may yield improvements in accuracy and lead to better separation of atmospheric delay and clock parameter estimates. Although there is a need for a VLBI network dedicated to geodetic applications, correlator centers can efficiently process both geodetic and astronomic VLBI

observations, and it appears that both communities can and should collaborate on the development of future generations of VLBI instrumentation.

(2) **VLBI observations should be transferred from the observing stations to the correlator center(s) using high-speed communication systems.** A small, but growing, number of VLBI sites are already using high-speed communication systems to transfer data. Using electronic data transfers can reduce the delays in processing "e-VLBI" observations to hours. Shorter delays would reduce the dependence on prediction models for determining the Earth's orientation, which is particularly important for deep space tracking and military uses. New correlator designs, possibly including widely-distributed correlators rather than a single, central location, as well as more automated data processing may be required to handle the anticipated higher data rates.

(3) VLBI data processing and products are not well integrated into geodetic products generated by other systems, though integrated products could improve the accuracy of VLBI results. **VLBI data analysis centers should consider using products from GNSS/GPS data analyses, such as polar motion and atmospheric delay estimates, in the generation of VLBI products.** The combined analysis would aid in terrestrial reference frame realization using VLBI networks with a small numbers of sites. The multi-look angles available with GNSS/GPS observations also could assist in accounting for atmospheric delays in VLBI processing, and the combined analyses would aid in integrating the VLBI analysis centers into the GNSS/GPS community.

GNSS/GPS

GPS[1] is now ubiquitous in civilian life, but it also provides a critical component of the geodetic infrastructure. GPS operates by broadcasting predetermined coded signals, including predicted satellite positions from multiple dedicated satellites, and then correlating those signals with internally-generated versions of the same signals inside GPS receivers on the ground (Figure 4.3) or in other platforms, such as vehicles, ships, planes, or spacecraft. This correlation is used to measure the distances between the satellites and the receivers; given prior knowledge of satellites' positions in space, the user's time and position are subsequently determined with respect to the terrestrial reference frame (e.g., WGS 84 or ITRF). For more precise applications, geodetic GPS receivers track the carrier signal directly in addition to the codes, enabling measurements with a precision of a few millimeters. The existing GPS infrastructure may be broken down into three basic areas: (1) military operations that maintain the system and generate broadcast satellite orbital position and timing data (i.e., ephemeris); (2) infrastructure that has been installed primarily to address scientific questions; and (3) other networks that have been installed to support civil engineering and surveying projects. The latency of data distribution from these networks varies between real-time transmissions of data to several month-long lags for scientifically important locations lacking easy communications links.

There are thousands of GPS receivers distributed around the world, and the sizes of the networks controlled by single entities vary greatly. The Operational Control Segment network used to generate the broadcast ephemeris data for civil and military navigation is probably the smallest but most secure, with just six Air Force stations and enhanced by eleven NGA stations distributed around

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[1] While this section focuses on the United States' GPS, it is expected that both scientific and civilian applications will expand to routinely include other international GNSS systems such as the current GLONASS system and the future Galileo and COMPASS systems.

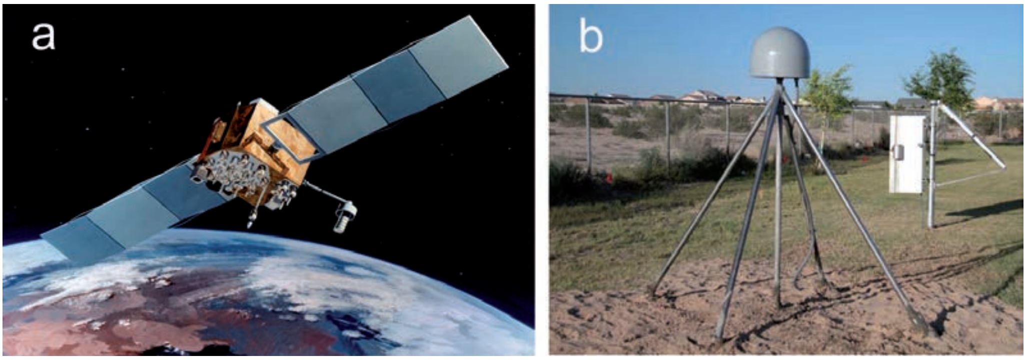

FIGURE 4.3 (a) An illustration of a Block-IIF GPS satellite and (b) a geodetic GPS receiver in San Luis, Arizona. SOURCE: Image courtesy of the United States Air Force (right) and photo courtesy of the Plate Boundary Observatory, the geodetic component of EarthScope, operated by UNAVCO and funded by the National Science Foundation (left).

the world. The network coordinated by the International GNSS Service (IGS), which provides the GPS component of the ITRF, consists of approximately 360 active stations (see Figure 5.1). The largest scientific network in the United States is the Plate Boundary Observatory (PBO) operated by UNAVCO for the National Science Foundation under its EarthScope Project. This network contains more than 1,100 high-accuracy GPS stations including 875 new stations built by the PBO and an additional 200 stations upgraded from networks that existed before the development of the PBO in 2004. Other scientific networks in the United States include the Bay Area Regional Dense array (BARD) near San Francisco Bay, the Pacific Northwest Array (PANGA), and others. These networks add approximately another 300 stations to the scientific networks. Within the United States, the largest network in support of surveying applications is the Continuously Operating Reference Station (CORS) network coordinated by the National Geodetic Survey (NGS). The stations in this network are operated by many different entities, but the distribution and archiving of data is carried out by the NGS. The NGS also sets the standards required for stations that are to be part of the CORS network. Currently, there are about 1,600 stations listed as CORS sites; many of these are also used as scientific stations.

Two major developments are occurring that will affect future applications of these GPS networks: (1) there is an increasing trend toward real-time access to high-sample rate data (one hertz and higher); and (2) new GNSS satellites are being developed that will add many more satellites and data types to the existing constellations. The transition to real-time data collection and dissemination is driven largely by the surveying community and industry, which can use real-time data to increase productivity in the field and improve vehicle tracking and navigation on local and global scales, respectively. In addition, the scientific community can use these data for developing warning systems for tsunamis and volcanic eruptions. It is expected that more GPS stations will be converted to real-time operation to support these types of activities. These new real-time applications affect the costs of network operations because they require continuously-operating data streams and the archival of high-rate data streams. On the other hand, real-time data are valuable for multiple uses, providing a broad community that can support the costs of these networks. In southern California, the maintenance of some of the real-time, high-rate stations in the Southern California Integrated GPS Network is supported by surveying groups who use the data. These maintenance efforts are coordinated through the California Spatial Reference Center.[2]

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[2] California Spatial Reference Center Website: http://csrc.ucsd.edu/

The other development that will affect existing GNSS/GPS networks is the transition from GPS-only receivers to combined GNSS/GPS receivers. Combined GPS-GLONASS receivers are now readily available and deployed by the IGS and for commercial applications. The current GLONASS constellation numbers 21 operational satellites with three more scheduled for launch in September 2010 to complete the nominal 24-satellite constellation. But, the largest impact may come from the European Galileo satellite system. When fully deployed, the Galileo system will be of similar size to the GPS system with 30 satellites in medium-Earth orbit. Existing GPS receivers will need to be replaced or upgraded, and antennas may need to be replaced to handle the new frequencies to be broadcast by Galileo. Even within the GPS network new antennas may be required to receive the full signal bandwidth, including additional signals that will be transmitted in the future at new frequencies. New antennas will need to be carefully calibrated to reduce systematic changes in the geodetic reference system caused during the transition.

Several system enhancements are needed to support the current and future scientific requirements and high-precision applications for GNSS/GPS. The GPS network must be upgraded to enable one millimeter post-processing positioning precision (24 hour averaging), 10 millimeter near real-time precision (few second latency), and 10 millimeter positioning precision for low-Earth orbiting satellites. The two main aspects of infrastructure development to achieve these objectives will be upgrading the GPS network equipment and distribution to meet the accuracy specifications and upgrading the GPS stations, data communications, and data processing infrastructure to enable high-precision, real-time positioning nationwide. The former requires upgrades to many stations to ensure stability (correct monumentation) and a good electrical environment (suppression of multipath). The latter could be achieved by signal processing techniques (rapid carrier phase ambiguity resolution), which would be strongly enhanced by spacing stations approximately 50 kilometers apart to cancel common errors between the user's receiver and the nearest network receivers. In addition, almost all GPS receiver sites will need to be upgraded in order to take advantage of signals from new GNSS systems as they come on line. Although significant technological development is required to turn current prototypes into operational systems, the barriers to these developments are a lack of systematic coordination and funding rather than technological barriers.

Significant infrastructure development, inter-agency coordination, and transfer of technology will be needed to achieve these goals. On the national scale, the current GPS network to serve high-precision applications is actually a collection of networks operated by different federal agencies including NGS, NSF, USGS, and NASA. In addition, NASA contributes to the global GNSS/GPS network operated under the IGS for precision orbit determination and for reference frame realization in order to meet scientific objectives. The global network is essential to meeting precision requirements on the national scale and so must be considered an essential part of the national geodetic infrastructure.

The various GPS networks operated by agencies of the United States are heterogeneous in terms of quality of instrumentation, site stability, and multipath environment. This is partly a result of history as the network has grown over the past 20 years and partly due to differences among various agency missions and funding models for the networks. For example, NASA has long supported the global network, which means that much of the equipment is aging, and the early engineering designs were not optimal for site stability and multipath environment. As another example, the CORS network was developed largely by accepting stations that were operated by local and regional entities (such as counties) with the result that there is little control or consistent knowledge of the station configurations, leading to a broad range of data quality. The USGS is a user of the GPS infrastructure, but it also has its own regional networks for research on seismic hazards. NSF (through UNAVCO) operates one of the largest and most recently-added networks (containing approximately 1,100 stations), but NSF has funded this network for only the duration of the EarthScope program.

> **Recommendation: The United States should significantly strengthen the GPS network by upgrading the instrumentation, monumentation, and technology. In addition, there should be greater coordination among the various U.S. agencies to develop strategies for meeting the needs of multiple agencies, as well as for long-term site maintenance, upgrade, data flow, and response to technological innovation.**

Such coordinated planning also could significantly reduce redundancies that are caused when an agency constructs networks only to meet its own needs or when agencies are not aware of the activities of other agencies.

With regard to data processing, there are currently several agencies and universities that routinely process data from the various high-precision GPS networks using custom software. Some are official analysis centers for the IGS. These include NGS, NASA's Jet Propulsion Laboratory, the University of California at San Diego's Scripps Institution of Oceanography, and the Massachusetts Institute of Technology. The IGS is currently conducting a "Pilot Project" for real-time, high-precision positioning.

> **Recommendation: Recognizing the importance of data-processing capabilities and activities to the national interest, the United States should continue to support these real-time, high-precision operations with a long-term view (not only for research and development).**

The IGS model promotes continuous innovation and improvement of product quality; as such, a service oriented approach is needed to address development and operation of the GPS network and the national geodetic infrastructure in general.

Satellite and Lunar Laser Ranging (SLR and LLR)

Laser ranging is a technique used to measure the time it takes for ultra-short laser pulses to reach retroreflector arrays on satellites or the moon and reflect back to Earth. The laser pulse is focused to a narrow beam by a telescope aimed at a satellite or the moon, and the return signal (in some cases as low as a single photon) is captured by the same telescope or by a larger, more sensitive parallel telescope (see Figure 4.4). Because the laser beam is so narrow, the orbits of the satellites or the moon must be predicted accurately and the telescopes must be pointed precisely in order for the telescopes to track their targets. Unlike radiometric techniques like VLBI, laser ranging only can operate when the sky is clear or through very thin clouds. However, the optical frequencies are much less susceptible to refraction from water vapor in the atmosphere. The precision of laser ranging has improved from a few meters in 1964 to a few millimeters today with centimeter-level absolute ranging accuracy (See Box 5.1 for a discussion of precision and accuracy). Achieving ranging accuracy at the millimeter level is an important challenge as the laser ranging community strives to improve the quality of the data.

SLR stations are operated by a variety of institutions around the world that cooperate to provide a global tracking data set for approximately 30 satellites (see Figure 5.1). Laser ranging data and analysis activities are managed by the International Laser Ranging Service (Pearlman et al., 2002). Most of the collected data are available within an hour of acquisition. Laser ranging data are used to define and maintain the ITRF (Altimimi et al., 2007), to observe temporal variations of Earth's gravity field (Cox and Chao, 2002; Cheng and Tapley, 2004), to determine Earth and lunar-orientation parameters and other fundamental physical constants for Earth, and to perform tests of general relativity (Ciufolini and Pavlis, 2004). Laser ranging also has pro-

FIGURE 4.4 Lunar laser ranging by the McDonald Laser Ranging System. Lasers are aimed at retroreflectors left on the moon by the Apollo and Lunokhod missions providing range measurements accurate to a few centimeters. SOURCE: Courtesy of R. Ricklefs, McDonald Observatory.

vided a 30-year history of geodetic information (long-wavelength gravity, geocenter, and plate motion), is used to determine or verify centimeter-precision satellite orbits (Exertier et al., 2001), including ongoing altimeter (ERS-2, GFO, Jason-1, Jason-2, and ICESat) and gravity (CHAMP, GRACE) missions; and continues to provide long-wavelength gravity variations to supplement gravity missions such as GRACE.

LLR is currently performed at stations in Apache Point, New Mexico, Grasse, France, and McDonald Observatory, Texas. However, the Apache Point station, which was designed for millimeter-level accuracy is in limited operation. The Grasse site has recently restarted lunar observations after being out of operation for several years for upgrades and refurbishment. An SLR station in Matera, Italy is capable of lunar ranging but has not yet initiated a lunar observing program. In addition to performing LLR using two-way ranging to the retroreflector arrays on the moon, experiments have begun that are attempting one-way laser ranging to the Lunar Reconnaissance Orbiter.

An ongoing concern with the SLR network is the lack of uniform coverage and performance. Roughly 80 percent of the SLR tracking on the LAGEOS satellites (used for determining the ITRF) is from the northern hemisphere, and only about a third of the total tracking is from the western hemisphere. Furthermore, tracking can vary greatly from station to station depending on weather conditions and staffing resources (see Figure 4.5). Among the stations that provided more than 100 passes

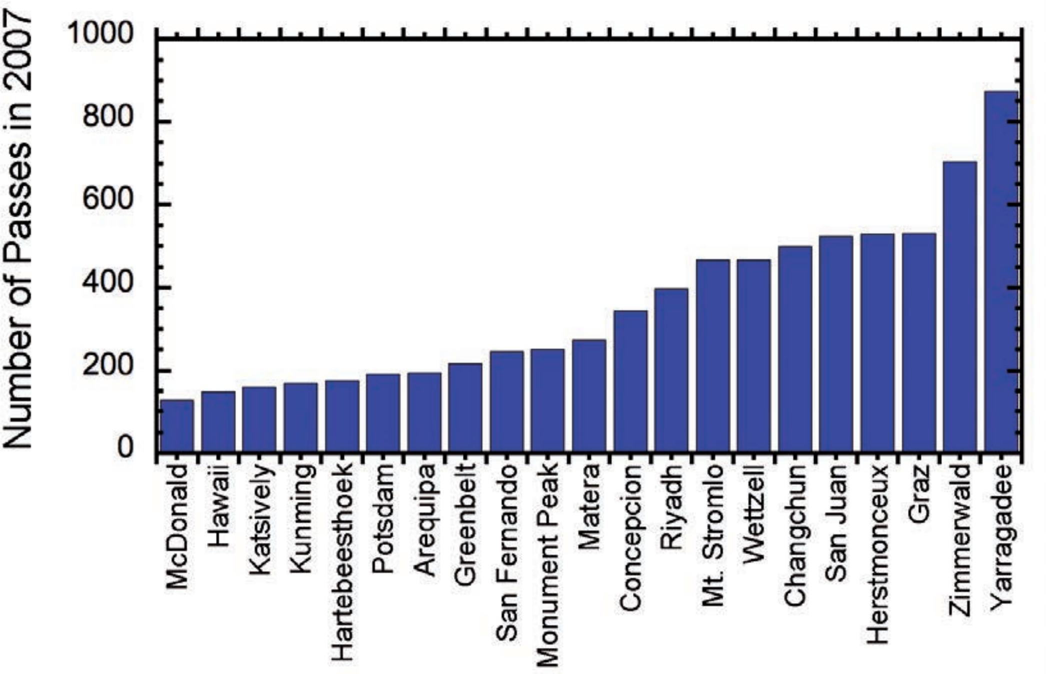


FIGURE 4.5 The number of passes obtained during 2007 from the SLR network for the altimeter satellite Jason-1 (only stations with at least 100 passes are shown), illustrating the significant range between stations in terms of data yield. SOURCE: Courtesy of John Ries.

for the Jason-1 altimeter satellite during 2007, the U.S. sites all fall in the lower half. Increasing the data yield from lower-volume sites, filling in the gaps in the SLR tracking network, and improving the overall balance in the station distribution are critical goals for the SLR system. In addition, the SLR network is threatened by reductions in operations or outright station closures due to considerable operation costs. The segment of the global SLR network that is operated by the United States is at risk of failure because the physical infrastructure is aging and many of the trained personnel in its small workforce are nearing retirement age.

Several significant enhancements are required for the next generation of SLR systems to improve data quality and reduce the cost of operation. Perhaps the most important needed improvement is to make the tracking equipment capable of fully autonomous operation yet retain the ability to acquire tracking for satellites up to GNSS/GPS altitudes. A prototype for such a system has been developed and is being tested at the Goddard Geophysical and Astronomical Observatory in Greenbelt, Maryland (a "fundamental" site where multiple geodetic techniques are co-located). In addition, multi-kilohertz firing rates, improved epoch timing, more stable ranging calibration, and operating in the single photon regime will reduce random and systematic errors for laser ranging. New applications of next-generation laser tracking stations include kilohertz-scanning of satellite surfaces (to determine the spin axis and rotation rate of spherical satellites) and atmospheric seeing measurements along the laser beam (to provide information on atmospheric turbulence). Kilohertz time transfer techniques are currently being tested on the Jason-2 mission with the Time Transfer by Laser Link (T2L2) experiment where one picosecond stability over several minutes may be achievable.

> **Recommendation: The United States should make a long-term commitment to deploy a new generation of SLR tracking stations capable of high-precision, high-rate, eye-safe, autonomous operation. At a minimum, these next-generation SLR tracking stations should be deployed at the four current United States tracking sites (Haleakala, Monument Peak, McDonald Observatory, and Greenbelt) to retain and extend the value of these sites for long-term terrestrial frame determination. International cooperation to improve the geographic coverage of the global SLR network and maximize the value of the U.S.-operated sites is also recommended.**

To enable lunar and interplanetary applications there is also a need to upgrade more laser ranging stations to lunar ranging capability, and progress should continue in the area of laser transponders to the moon and other planets.

Doppler Orbit Determination and Radiopositioning Integrated by Satellite (DORIS)

The DORIS system is a French civil precise orbit determination and positioning system. As illustrated in Figure 4.6, DORIS consists of a network of terrestrial beacons that transmit signals to instruments onboard a satellite including an antenna, radio receiver, and an ultra-stable oscillator that provides the reference frequency standard. The onboard receiver compares the signal emitted by

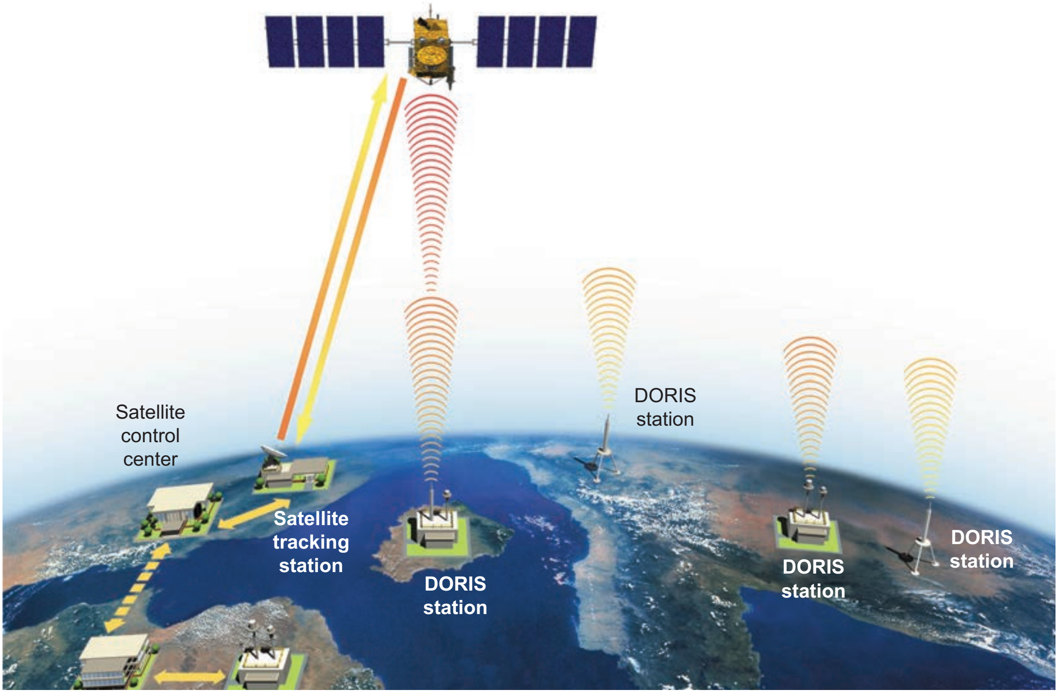


FIGURE 4.6 Schematic of the DORIS system. Ground beacons broadcast omni directionally and require only steady power. Some, called "master" beacons, are connected to high-precision time standards and can upload commands to a DORIS receiver onboard a satellite. The tracking data collected onboard is transmitted to the ground to be processed and distributed by SSALTO (Segment Sol Multimission Altimetry and Orbitography) operated by CNES. SOURCE: © CNES/ill. David Ducros.

the ground beacon against the onboard frequency standard. Because of the satellite's velocity, the incoming signal will appear to be shifted in frequency causing a "beat" with respect to the satellite's internal clock. Measurements of the number of beat cycles can be used to determine the velocity of the satellite, which is then incorporated with satellite orbit dynamics to determine the distance between the satellite and the ground beacon. DORIS is optimized for precise orbit determination with global coverage and all-weather measurements. The system was designed and developed by the Centre National d'Etudes Spatiales (CNES, the French Space Agency) in partnership with the Groupe de Recherche de Géodésie Spatiale (the French space geodesy research group) and the Institut Géographique National (the French national mapping agency). It was developed primarily for precise orbit determination of altimeter missions and, consequently, also for geodetic ground station positioning. The DORIS products and activities are managed by the International DORIS Service (IDS) (Tavernier et al., 2006).

The DORIS ground segment currently consists of 57 beacons with a remarkably uniform coverage around Earth (see Figure 5.1). This even coverage was established in part, because in the early development of the system, interference would occur within the receiver if the transmitters were close to each other. The new receivers, however, no longer have this limitation and can track several beacons at the same time. Nevertheless, CNES has strived to distribute the beacons evenly for the best possible performance for satellite orbit determination. One of the advantages of DORIS is that all observations are collected centrally onboard the satellites and no ground links are necessary making it possible to deploy beacons in remote and inhospitable areas (for example, islands in the southern hemisphere and Antarctica). As the ITRF attempts to achieve a no net rotation system (see Chapter 5), sites distributed over many locations on different plates is important. The scientific contributions of DORIS also increase as the time span increases providing a useful "lever arm" for station velocity determination. Some DORIS sites have been occupied since the early 1990s. The DORIS network is constantly being maintained with renovations at many of the sites to upgrade the transmitters or improve the stability of the antennas.

The DORIS network is well distributed, and the commitment of CNES to the maintenance of the system appears to be strong. Currently, there are six satellites carrying DORIS receivers, and it has been demonstrated that the DORIS positioning performance improves significantly when using four or more satellites (Altamimi and Collilieux, 2010). Consequently, installing the DORIS system on more satellites will significantly improve the DORIS contribution to positioning and geodesy applications.

> **Recommendation: The United States should deploy, where possible, DORIS receivers on U.S. low-Earth orbiting missions to enhance the DORIS positioning performance and the contribution of DORIS to the ITRF.**

Future altimetry missions could benefit from carrying not only a DORIS receiver but also SLR reflectors and GNSS/GPS receivers to improve the inter-calibration between the three systems and for orbit precision verification.

Terrestrial (Ground and Airborne) Gravity

Differences in the height of land above the geoid—orthometric heights—determine the direction of water flow. Thus knowledge of orthometric heights is critical for applications such as estimating floodplain extent, evaluating storm surge hazards, and designing aqueducts. At present, orthometric heights in the United States are determined by tying local surveys into a network of 600,000 leveling monuments, which were established over the past century by the NGS. This network was built up over decades using a variety of instruments and procedures with varying data quality and biases. That network has been steadily degrading as monuments are damaged or destroyed or experience unmonitored vertical motion. Today, leveling is a time-consuming, labor-intensive, and expensive surveying technique, and it is impractical to continue to maintain the existing monument network. Instead, the NGS has proposed that the United States switch to a method in which orthometric heights are determined using GNSS/GPS to measure geometric heights and then subtracting modeled geoid heights. This method is faster, less expensive, and more accurate than leveling. However, it requires an accurate, high-resolution geoid model.

The geoid is the level surface (a surface of constant gravitational potential) that, over the open ocean, approximates mean sea level. Extending the geoid to land was typically accomplished with ground-based leveling techniques, but is now augmented with global gravity field models from space techniques. Figure 4.7 illustrates the geoid over the continental U.S. based on the recent NGS geoid model GEOID09 (Roman et al. 2009) where the range in geoid height varies by approximately 50 meters. Geoid models created from satellite observations alone have spatial resolutions no better than 100-200 kilometers (see Box 4.1). In order to develop a geoid model that is accurate to the centimeter level and with a spatial resolution approaching the few kilometer level over the continental United States, it is necessary to record millions of ground or airborne gravity measurements that can be combined with a global satellite gravity field. Historical airborne gravity observations collected before aircraft were equipped with GNSS/GPS typically had such large biases and systematic errors that most geodesists have chosen not to use them in deriving regional geoid models. The NGS has embarked on the GRAV-D project to determine the geoid with accuracy at the 2-centimeter level for much of the country with high priority assigned to the coastlines of the continental Untied States and American island holdings (see Box 5.2). An accurate geoid is particularly important along the coastlines because many coastal areas are flat enough that small errors in height estimates can lead to mismodeled flood hazard predictions.

The geodetic community has recognized the potential of using highly precise gravity measurements to monitor vertical crustal motions and subsurface mass movements, particularly in combination with GNSS/GPS measurements of height changes (Wahr et al., 1995). NOAA established

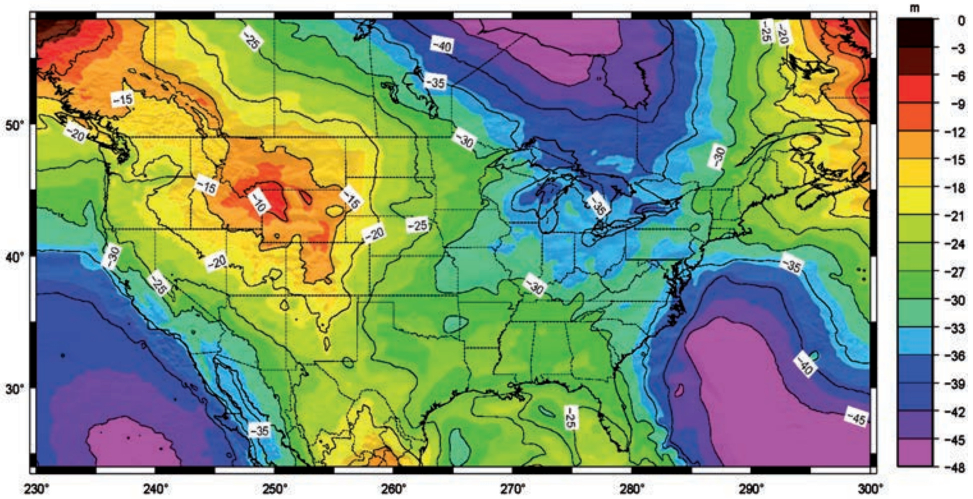
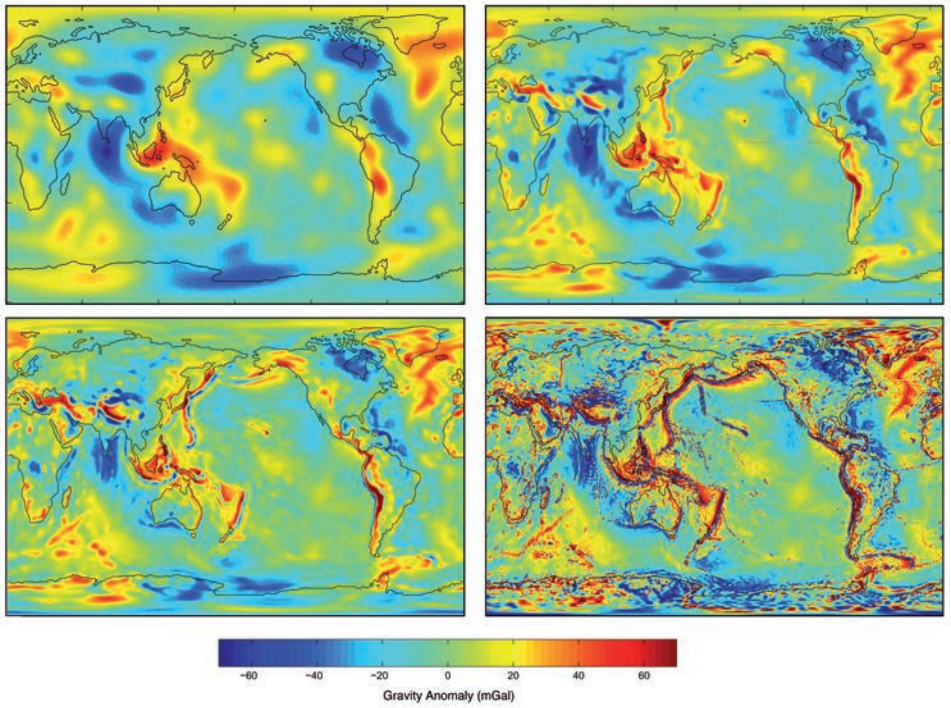


FIGURE 4.7 The geoid height over the continental United States based on GEOID09. Negative values indicate that the geoid is lower than the reference ellipsoid (positive values, above). For purposes of determining the direction of water flow, the absolute height of the geoid is not important but, rather, it is the slope in the geoid relative to the land surface that matters. GEOID09 is based on EGM2008 (Pavlis et al., 2008a), which in turn relied on GRACE for the long-wavelength component of the gravity field model. SOURCE: NGS (http://www.ngs.noaa.gov/GEOID/GEOID09/).

BOX 4.1
MEASURING EARTH'S GLOBAL GRAVITY FIELD

Normal gravity is defined as the value of gravity for a perfectly smooth oblate Earth, and the "gravity anomaly" is a measure of how actual gravity deviates from this idealized value. Maps of these anomalies reflect the changes in the Earth's mass distribution, particularly in the crust, revealing many features associated with plate tectonics.

The launch of the joint United States/Germany Gravity Recovery and Climate Experiment (GRACE) in 2002 dramatically improved the ability to measure Earth's global gravity field from space. Prior to the GRACE mission, the resolution of the gravity field from space was limited to relatively long wavelengths



Images (from left to right, top to bottom): (a) Just 111 days of data from GRACE dramatically increased the resolution of gravity data. (b) With four years of data, the resolution has now been further increased. (c) There is a limit to the resolution that can be achieved from space, however. For more detailed gravity maps, terrestrial gravity data must be incorporated. Over land, expensive surface gravity surveys must be conducted. Over the oceans where the sea surface conforms closely to the Earth's gravity field at the shorter wavelengths radar altimeter satellites have provided detailed information. (d) When terrestrial gravity data are included the resolution of the gravity field model is on the order 10 kilometers in many areas. SOURCE: The University of Texas Center for Space Research.

a gravity observatory near Boulder, Colorado equipping it with a cryogenic (superconducting) gravimeter and an absolute gravimeter. The absolute gravimeter was commercialized, and scientific organizations in nations around the world purchased the U.S.-manufactured instruments and began ambitious cooperative observing programs. The current programs using these absolute gravimeters are organized under the International Gravity Field Service, a new "umbrella" service of the International Association of Geodesy coordinating the collection, archiving, and distribution of gravity-related data, software, and information.

> **Recommendation: Because absolute and cryogenic gravity observations, when combined with GNSS/GPS observations, offer unique insight into glacial rebound and subsurface mass movement, the United States should reinvigorate its once world-class gravity program.**

Tide Gauges

The global tide gauge network is important for geodesy in several respects. Historically, tide gauge data helped in defining geodetic reference heights ("datums") at country scales. Recall that elevation or orthometric height is defined relative to mean sea level. In addition, tide gauge data provide information on ocean tides and long-term variations in sea level. Tide gauge data are especially critical for calibrating in-orbit altimetric satellites. For example, using a set of about 50 high-quality tide gauges distributed around the world Mitchum (1998) detected an artificial drift in the TOPEX/Poseidon altimeter caused by an algorithm error. Since then, drifts of instruments (in particular, radiometers used for measuring atmospheric water vapor) onboard altimeter satellites are routinely monitored by systematically comparing altimetry-derived and tide gauge-based sea level variations (see Mitchum, 2000; Nerem and Mitchum, 2001). Using GNSS/GPS-corrected tide gauges, Wöpplemann et al. (2009) estimated that regional sea level trends were different using the ITRF from the year 2000 versus the ITRF from the year 2005 due to the systematic differences between the two ITRF solutions.

The largest database of monthly and annual mean sea level records from tide gauges is the Permanent Service for Mean Sea Level (PSMSL) (Woodworth and Player, 2003). Although the PSMSL includes data from approximately 2,000 sites in about 200 nations, the records are inconsistent in terms of data length and quality. Only about 10-20 percent of this data set is useable for long-term sea level studies. For oceanographic, climate, and coastal sea level research, a core network of 290 high-quality PSMSL stations has been designed and is called the Global Sea Level Observing System (GLOSS), which is coordinated by the Intergovernmental Oceanographic Commission (Woodworth and Player, 2003). The distribution of the GLOSS network is presented in Figure 4.8.

One of the primary uncertainties in tide gauge calibration is the vertical motion of the ground at individual tide gauges. Mitchum (1998) proposed to design a dedicated network of globally-distributed tide gauges with GNSS/GPS correction for land movement that would be able to detect altimeter drift errors of one millimeter/year for a three-year period. Since then, tide gauges have proven to be extremely useful for calibrating satellite altimetry systems. Nevertheless, accurate knowledge of vertical land movements at tide gauge sites is still lacking. A significant part of the 0.4-0.6 millimeter/year uncertainty in the altimetry-derived rate of global mean sea level rise comes from reference frame errors or from the lack of any measurement of the vertical motions of the tide gauges used for calibration (Nerem and Mitchum, 2001; Beckley et al., 2007).

In 2001, the International GNSS Service established a pilot project called TIGA (GPS TIde GAuge bench mark monitoring) (Bevis et al., 2002) with an objective of establishing the required research infrastructure (observing stations, data centers, and dedicated analysis centers) for determining vertical motions at tide gauges to an accuracy of better than one millimeter/year within a

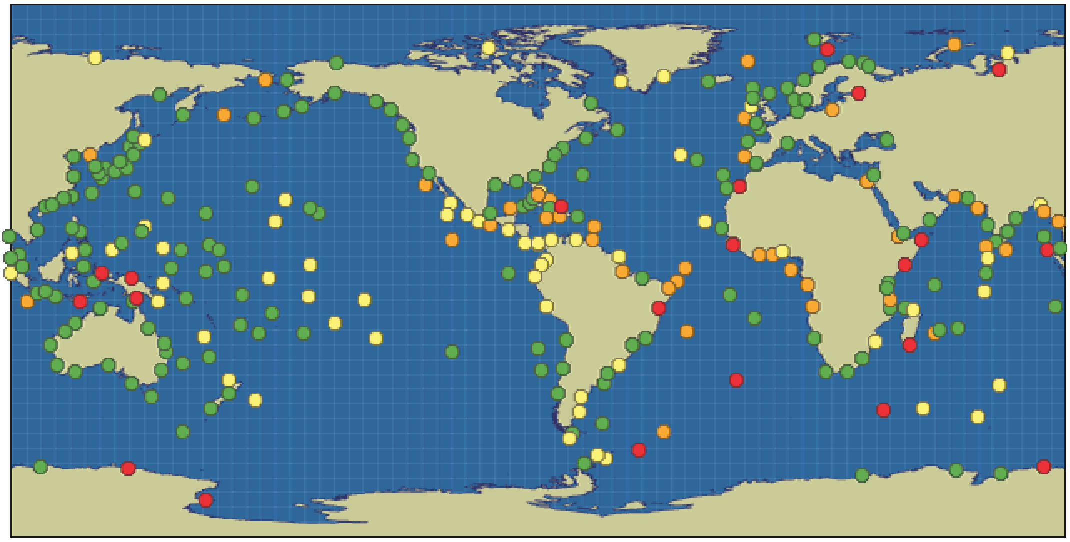


FIGURE 4.8 The GLOSS network of tide gauges. Green dots represent "operational" stations for which the latest data were collected in 2003 or later. Yellow dots represent "probably operational" stations for which the latest data were collected within the period 1993-2002. Orange dots represent "historical" stations for which the latest data were collected earlier than 1993. Red dots represent stations for which no PSMSL data exist. SOURCE: Courtesy of the Permanent Service for Mean Sea Level and the Global Sea Level Observing System (GLOSS).

decade. Determining local vertical rates at such a level of accuracy remains challenging, however, partly because of challenges involved in maintaining the stability of the reference frame and maintaining frequent leveling (at least annually) between the GNSS/GPS antenna and the tide gauge in places where these are not closely co-located. Regular leveling surveys are often neglected over time, particularly in places where the distance between the two instruments is large. Where this distance is more than one kilometer leveling ties error can be large and become a significant part of the error budget. Thus, except for sites with well-established local or regional stability, GNSS/GPS stations more than one kilometer from the tide gauge cannot really be considered as co-located. In many cases the GNSS/GPS station may need to be located on or very close to the tide gauge to represent its vertical motion accurately

> **Recommendation: The Committee recommends that the United States support the TIGA initiative and similar efforts to accurately determine the vertical motion of reference tide gauges.**

EARTH OBSERVATION SATELLITES

Artificial satellites are an essential component of the precise geodetic infrastructure. These satellites provide the link between the global reference frame and the end user of geodetic products. Indeed, without the satellite component there would not be an ITRF. The artificial satellites can be broadly divided according to the measurements they provide (Table 4.1). GNSS/GPS satellites are used for precise point positioning anywhere on or near Earth's surface (including low-Earth orbit). Satellite altimetry (radar or laser) provides elevation profiles of ocean, land, and ice surfaces at accuracies needed to monitor, for example, global mean sea level or polar ice sheet changes. Inter-

TABLE 4.1 Geodetic Satellites and Applications

Technology Orbit Height	**Type**	**Agency**	**Date**	**Applications**
		Global Navigation Satellite Systems (GNSS)		
GPS 26,600 km	Global Positioning System	DoD	1980-present	Precise positioning, solid Earth, hydrology, glaciology, atmosphere, ionosphere, natural hazards
GLONASS 19,100 km	GLObal NAvigatsionnaya Sputnikovaya Sistema	USSR/Russia	1982-present	
Galileo 23,300 km	Global Navigation Satellite System	ESA	testing	
Beidou-2 or COMPASS 36,000, 21,500 km	Regional/Global Navigation Satellite System	China	2007-present	
		Satellite Altimetry		
SeaSAT 800 km	Radar	NASA	1978	Oceanography, sea level rise hydrology, glaciology, marine gravity bathymetry
GeoSAT 800 km	Radar	DoD	1985-1989	
TOPEX/Poseidon 1330 km	Radar	NASA/CNES	1992-2006	
Jason-1/2 1330 km	Radar	NASA/CNES	2001-present	
ERS-1/2 780 km	Radar	ESA	1992-present	
ENVISAT 780 km	Radar	ESA	2002-present	
ICESAT 600 km	Laser	NASA	2003-2010	Glaciology, hydrology oceanography
CryoSAT-2 720 km	SAR/Interferometric Radar	ESA	2010-present	
		Interferometric Synthetic Aperture Radar (InSAR)		
ERS-1 780 km	C-band, VV polarization	ESA	1992-1996	Solid Earth, hydrology, glaciology, oceanography, geotechnical, natural hazards
ERS-2 780 km	C-band, VV polarization	ESA	1996-present	
JERS-1 570 km	L-band, HH polarization	JAXA	1992-1998	

TABLE 4.1 Continued

Technology Orbit Height	Type	Agency	Date	Applications
RADARSAT-1 800 km	C-band, HH polarization	CSA	1995-present	
SRTM 233 km	C-band, fixed baseline interferometer, HH,HV,VH,VV	NASA	2000	
ENVISAT 780 km	C-band, VV+VH, HH+HV	ESA	2002-present	
ALOS 690 km	L-band, quad-polarization	JAXA	2006-present	
RADARSAT-2 800 km	C-band, quad-polarization	CSA	2007-present	
TerraSAR-X 514 km	X-band, quad-polarization	DLR	2007-present	
COSMO-SkyMed 619 km	X-band, quad-polarization	ASI	2007-present	
		Geodetic Missions (Reference Frame, Gravity or both)		
Starlette/Stella 812 km	Laser satellite	CNES	1975/1993-present	
LAGEOS-1/2 5620 km	Laser geodynamics satellites	NASA	1976-present	
Etalon-1/2 19,100 km	Laser satellites	Russia	1989-present	
CHAMP 350 km	Challenging Minisatellite Payload	DLR	2000-present	
GRACE 460 km	The Gravity Recovery and Climate Experiment	NASA/DLR	2002-present	
GOCE 250 km	Gravity field and steady-state Ocean Circulation Explorer	ESA	Launched 2009	

Agencies: CNES – National Space Study Center (France); CSA – Canadian Space Agency; DLR – German Aerospace Center; DoD – Department of Defense (USA); ESA – European Space Agency; JAXA - Japan Aerospace Exploration Agency; NASA – National Aeronautics and Space Administration (USA); ASI - Italian Space Agency

Abbreviations: HH (Horizontal transmit, Horizontal receive); HV (Horizontal transmit, Vertical receive); VH (Vertical transmit, Horizontal receive); VV (Vertical transmit, Vertical receive).

SOURCE: Modified from Wdowinski and Eriksson, 2009.

ferometric Synthetic Aperture Radar (InSAR) is a swath-mapping radar used to measure topography and topographic change over ocean, land, and ice surfaces. Finally, gravity missions measure the spatial and temporal variations in Earth's gravity field associated with water redistribution between the atmosphere, oceans, groundwater, and ice sheets.

These satellites both rely on and help to define the ITRF. Their contribution to the reference frame depends mostly on the altitude of their orbit. Satellites in high-altitude orbits (higher than 5,000 kilometers) fly well above the outermost atmosphere of the Earth, and ground-based tracking of these high Earth-orbiting satellites is an essential component in defining and maintaining the accuracy of the ITRF. These satellites contribute to the definition of the location of Earth's center of mass, Earth's response to lunar and solar tidal forces, and the changes in Earth's shape due to post-glacial rebound, large-scale changes in ocean circulation, and ice melting in mountain glaciers and polar ice sheets.

Geodetic satellites generally require medium or high-precision orbits though the exact level of accuracy needed depends on the application. Three main types of tracking systems are used. First, radar tracking of all orbiting material provides orbital accuracies at the 100-meter level, which is needed for space reconnaissance and collision avoidance. Second, much more precise tracking (1-10 centimeters) can be achieved by including a geodetic-quality GNSS/GPS or DORIS receiver onboard the satellite. These high-accuracy tracking systems are essential for most of the Earth science applications discussed in this report. Third, SLR offers a relatively inexpensive failsafe method of precise satellite tracking (to the centimeter level or better). Completely passive geodetic satellites such as LAGEOS, Starlette, Stella and Etalon, which will remain as stable orbiting reference points for hundreds or even thousands of years, are exclusively tracked by SLR. When multiple tracking systems are available they are often combined (with their data weighted according to performance) to provide the most accurate orbits. Alternatively, SLR tracking is sometimes withheld from the orbit solution to provide an independent assessment of the orbit accuracy. SLR data are unique in that they yield absolute range measurements between the ground and satellite independently of the orbit (some prior knowledge of the orbit is required only for "acquiring" the target satellite, that is, aiming the laser beam accurately). In contrast, for techniques like GNSS/GPS and DORIS estimation of all biases and corrections is not an independent procedure, but is instead an intrinsic part of the orbit solution. The use of SLR to verify the radial accuracy (height) of the orbit is especially critical for altimeter missions.

Though GNSS/GPS and DORIS are now routinely used for operational orbit determination on most geodetic satellites that require high precision orbits, SLR has proven to be vital as a backup tracking system. For example, the primary tracking aboard the European Space Agency's Earth Remote Sensing satellite (ERS-1) failed immediately after launch, and the GPS receivers aboard the Geosat Follow-on Mission (GFO) failed in spite of four-unit redundancy. Fortunately, both satellites had an optical corner cube to enable SLR tracking to achieve sub-decimeter accuracy orbits. Without this SLR backup, both missions would have been nearly complete failures. Another example is RADARSAT-1, which was launched without any precise tracking capability just after the development of InSAR. InSAR has revolutionized our images of earthquakes, volcanoes, and ice streams but relies on an orbit accuracy of one meter or better. Although RADARSAT-1 was launched just three years after ERS-1 and had a superior radar, it was rarely used for the interferometric investigations because of its lack of precise orbital information. It is absolutely essential for any geodetic satellite mission that at least one of the precise tracking systems (GNSS/GPS, DORIS, or SLR) is functioning or the mission may fail to achieve its objectives. Onboard tracking receivers cannot be repaired after the satellite is injected into orbit so every geodetic satellite needs to be equipped with an optical corner cube for backup SLR tracking.

INTERNATIONAL GEODETIC SERVICES

For each one of the four primary geodetic techniques (VLBI, SLR, GNSS/GPS, and DORIS), an international service coordinated within the International Association of Geodesy (IAG) organizes and coordinates the data that are acquired, manages the analysis of that data, and generates products for users. These services develop the necessary standards and conventions and encourage international adherence to those conventions in the processing of the data provided by each technique. These services are critical components of the geodetic infrastructure.

As an example, the International VLBI Service (IVS) is essential to acquiring the basic data since VLBI measurements must be coordinated between the various stations to observe the same radio sources at the same time. The stations cannot work independently, and each observing run must be planned in detail. The IVS interacts with the users of VLBI products to integrate VLBI into the global Earth observing system, sets performance standards for the observing stations, establishes conventions for data formats and products, and issues recommendations for analysis software. Finally, the IVS sets the standards for analysis documentation and institutes appropriate product delivery methods in order to ensure product quality and timeliness. The IVS consists of about 30 Network Stations acquiring high-performance VLBI data; three Operation Centers coordinating the activities of a network of network stations; six Correlators processing the acquired data, providing feedback to the stations, and providing processed data to the analysts; six Data Centers distributing the products to users and providing storage and archiving functions; 21 Analysis Centers analyzing the data and producing the results and products; eight Technology Development Centers developing new VLBI technology; and one Coordinating Center coordinating daily and long-term activities. This adds up to more than 75 components representing more than 30 institutions in 16 countries.

The International GNSS Service (IGS) is a collaboration of approximately 200 organizations comprising diversely funded government agencies, universities, and other groups around the world that contribute data and analysis capability for GNSS/GPS. The products generated by the IGS analysis centers are freely available and include core products such as precise orbits and clock corrections for GNSS/GPS satellites (currently GPS and GLONASS), and tropospheric and ionospheric parameter estimates. The IGS orbit products are available on time scales ranging from near-real-time and predicted orbits (ultra-rapid product) to the most accurate orbits (final orbit product), which are available with 2-week latency. Comparisons among the IGS analysis centers show that the IGS ultra-rapid orbits have an internal consistency of better than five centimeters, while the IGS final orbits currently have an internal consistency at the one to two centimeter level. Comparisons with SLR tracking of the two GPS satellites that have reflector arrays indicate an absolute orbit accuracy better than five centimeters. The IGS products, particularly the precise orbits and GPS clock solutions, have become integral in a wide variety of civil and scientific activities. Even U.S. government agencies commonly rely upon the routine availability of the IGS products although some of these agencies such as the National Geospatial-Intelligence Agency have the capacity to generate such products independently. It is now common for geodetic missions to operate a GNSS/GPS receiver on board their satellites for precision orbit determination, relying upon either the IGS orbits and clock solutions or the ground data collected by the IGS network for computing their own solutions. The IGS analysis centers also now provide the dominant contribution to the determination of the Earth's polar motion. Like the other services, the IGS sets antenna monumentation standards for the observing stations, establishes conventions for data formats and products, and issues recommendations for analysis models, constants, and procedures.

The International Laser Ranging Service (ILRS) provides satellite and lunar laser ranging data and their related products to support geodetic and geophysical research activities. Satellite tracking priorities are agreed upon by the ILRS to best reflect the tracking data needs of each mission and its overall contribution to the geodetic community with special tracking campaigns sometimes organized for particular investigations of limited duration. The ILRS analysis centers receive and process tracking data from one or more data centers for the purpose of producing ILRS products without interruption at an interval and with a time lag specified by the Governing Board to meet ILRS requirements. The analysis centers are committed to producing Earth orientation parameters on a weekly or sub-weekly basis, as well as other products, such as station coordinates, on a regular basis. This analysis also provides a second level of quality assurance on the global data set by monitoring individual station range and time biases.

The International DORIS Service (IDS) serves a similar function for the community that relies upon the DORIS technique. IDS distributes the tracking data and derived products, establishes conventions for data and product formats, and issues recommendations for analysis models. It interacts with CNES, the agency controlling the DORIS system, regarding opportunities to deploy DORIS beacons in geodetically useful or geophysically interesting locations.

The International Gravity Field Service (IGFS) is a new "umbrella" IAG service coordinating the collection, archiving, and distribution of gravity-related data, software, and information. It does not distribute the gravity data directly, but rather functions as a unifying service for the various gravity-related IAG services. The data of the IGFS services include satellite-derived global models; terrestrial, airborne, satellite, and marine gravity observations; Earth tide data; GNSS/GPS leveling data; digital models of terrain and bathymetry; and gravity field information from satellite altimetry. The IGFS coordinates the Bureau Gravimetrique International in Toulouse, France; the International Geoid Service in Milano, Italy; the International Center for Earth Tides in Papeete, French Polynesia; the International Center for Global Earth Models in Potsdam, Germany; and the International Digital Elevation Model Service in Leicester, United Kingdom.

Finally, the International Earth Rotation and Reference System Service (IERS) provides the main geodetic references needed by the astronomical and geodetic communities, which are the celestial and terrestrial reference frames, and the Earth rotation and orientation parameters connecting these two frames. The IERS products are generated by combining the products from individual geodetic techniques enabling the IERS to take advantage of the strengths and mitigate the weaknesses of the individual contributions. So that these individual contributions are consistent and at the highest level of accuracy, the IERS coordinates the geodetic conventions, models, and constants used in the analysis of the geodetic data. The IERS Conventions are updated regularly as the models, constants, and procedures are improved.

In addition to these organizational services, data centers provide archiving of and electronic access to basic geodetic measurement data and products. The Crustal Dynamics Data Information System, funded by NASA's Earth System Science Data and Services, provides access to the data from the VLBI, GPS, SLR, and DORIS techniques; the SLR data also is mirrored at the EUROLAS Data Center at the Deutsches Geodätisches Forschungsinstitut. The Physical Oceanography Distributed Active Archive Center, one of eight NASA Distributed Active Archive Centers, provides instrument data and derived products from a long list of oceanographic missions. It also is the U.S. distributor for the GRACE gravity mission data.[3] Internationally, most geodetic services coordinate their operations through the Federation of Astronomy and Geophysics Data Analysis Services of the International Council for Science (ICSU). In 2008, ICSU recognized the need to update this half-century old organization as well as the World Data Centers and to develop a new World Data System (ICSU-WDS). The process of building this global scale collaboration is ongoing.[4]

A common feature, but also a source of concern, of the geodetic services is that they are built on the voluntary international collaboration of organizations (universities, space agencies, and geodetic national institutions) with distributed functions (Central Bureaus, Analysis Centers,

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[3] JPL Data Catalog: http://podaac.jpl.nasa.gov/DATA_CATALOG/index.html

[4] ICSU-WDS Website: http://icsu-wds.org

Product Centers, Combination Centers, and other associated components). The current service components are primarily funded and maintained by their host countries on behalf of the scientific community. Research studies are undertaken by the participating institutions in order to produce the highest-quality products. Directing and Governing Boards of the services have the important role of reviewing the work of the different components of the service, coordinating their actions, and deciding policy. For the ILRS Central Bureau, the director, secretary, science coordinator, and two of the three analysis specialists are from the United States. For the IVS, the network and technology coordinators are from the United States, as are the Correlators and Operation Centers Representative. For the IGS, seven members of the Governing Board are from the United States, and NASA supports the IGS Central Bureau. This demonstrates that the various services are vulnerable to the vagaries of funding and support of the U.S. participants.

> **Recommendation: The United States should continue to participate in and support the activities of the international geodetic services (IGS, ILRS, IVS, IDS, IGFS and IERS) by providing long-term support for the operation of geodetic stations around the world and by supporting the participation of U.S. investigators in the activities of these services.**

In summary, the geodetic infrastructure, which supports myriad national and international interests in the Earth sciences, consists of geodetic networks (ground-based instruments and their attached GNSS/GPS receivers, radio telescopes, laser tracking stations, DORIS beacons, tide gauges, and gravity meters), geodetic platforms (satellites, aircraft, and other vehicles), the geodetic data processing and service centers and, of course, the geodesists themselves. Each component is a critical link in the chain from the raw data to the refined measurements and products (such as the ITRF described in Chapter 5). A failure in any component is a failure in the technique, and all the techniques are required to support the important scientific studies addressing such issues as global climate change and natural hazard understanding, prediction, and mitigation.

5

Geodetic Reference Frames and Co-Location Requirements

Modern geodetic methods have enabled the positions of geodetic stations to be determined within a well-defined frame of reference; as a result, the long-term movements of the Earth's surface can now be monitored at a level of approximately one millimeter per year. Dense networks of GNSS/GPS stations are used to map the strain in the Earth's crust at plate boundaries and to "observe" plate tectonics as they happen. The Earth's geometrical and gravitational shapes and its orientation in space are being monitored to determine the redistribution of fluids on or near the Earth's surface, including the ocean and atmosphere, the cryosphere, and the terrestrial hydrosphere. All of these scientific applications depend on a truly global reference system that only geodesy can provide. In addition, navigation systems, such as those based on GPS, are typically referenced to a specific reference frame. This chapter describes the importance of the International Terrestrial Reference Frame (ITRF) and its current level of accuracy, limiting factors, and requirements for future improvements. It also discusses the relationship between the global reference frame (represented by the ITRF) and regional reference frames.

The ITRF is the primary global spatial reference system in existence today, although other regional reference frames also have been developed. The ITRF is created and maintained, or "realized," by using geodetic observations to determine the positions and velocities of physical reference points on the Earth's surface, and matching them as closely as possible to the mathematical and physical properties of an idealized, or theoretical, frame. The reference points for the ITRF may consist of geodetic equipment on the ground, or fixed points within the geodetic instruments themselves.

The main physical and mathematical properties of a reference frame are the origin, the scale, the orientation, and the changes in these parameters over time. The "origin" of a reference frame is the zero point of the three Cartesian axes (i.e., X, Y, and Z), typically the center of mass of the entire Earth system. This point can be determined most accurately from the observations of satellite motion, as satellites naturally orbit about Earth's center of mass. The "scale" refers to the absolute distance between points in the network. It is a uniform scaling of all coordinates, with the result that a scale error in the reference frame results in a radial (height) error for all stations. Similarly, a scale-rate error results in an error in all vertical rates, a particularly insidious error that can, for example, significantly affect the interpretation of very small changes in sea level rise and in surface deformation due to tectonic plate dynamics. The "orientation" essentially refers to the definition of the zero point for longitude and latitude. Unlike origin and scale, which are determined directly by the geodetic observations, we are free to choose any point on Earth as zero longitude or zero latitude. We try to maintain consistency with the historical Greenwich meridian for zero longitude and Earth's equator as zero latitude, which is perpendicular to the Earth's spin axis, but these directions cannot be fixed due to plate tectonic motion and polar motion. Therefore, by convention the orientation of the ITRF is designed to maintain consistency with previous reference frames and specified by the requirement of no-net or zero-average rotation with respect to horizontal plate motion of the Earth's surface. This is difficult to realize in practice due to the limited number of sites distributed on the various continental plates, which are all moving above Earth's mantle and core.

Continuous, long-term geodetic observations are crucial if the ITRF is to account correctly for the complex movements of points on the surface of the Earth, so that we can characterize and model these movements precisely. In the absence of technique-specific systematic errors, and if all geophysical processes are accurately accounted for in the geodetic analysis, the ITRF properties should be stable over time (that is, they should not exhibit any drift or discontinuities over the time-span of the geodetic observations; see Box 5.1). Any deficiencies in the accuracy or continuity of the ITRF will limit the quality of science that it can support.

STABILITY AND ACCURACY OF THE ITRF

The stability and accuracy of the ITRF over long time periods is a primary limiting factor for understanding sea level change, land subsidence, crustal deformation, and ice sheet dynamics. Of these, a quantifying long-term change in sea level imposes the most stringent observation requirements. The ITRF constitutes the foundation connecting observations in space, time, and evolving technology, and provides the framework in which global and regional observations of sea level change can be understood and properly interpreted. A stable ITRF is required if sea level measurements at sub-millimeter accuracy made today are to be meaningfully compared with measurements made a decade from now. The ITRF also can be extended to regional and local studies in order to link multidisciplinary observations and ensure long-term consistency, precision, and accuracy (see Box 5.1). For the ITRF to accurately quantify long-term sea level change, the ITRF must be both accurate and accessible at the 1-millimeter level, with a stability of 0.1 millimeters per year.

Given that existing reference frames have not achieved this level of accuracy and stability, it is not surprising that one of the largest sources of error in the global characterization of long-term sea level variation is uncertainty in the ITRF. For example, a 2-millimeter-per-year error in the relative velocity between the Earth's mean surface and the Earth system's center of mass can result in an error as large as 0.4 millimeters per year in the determination of mean global sea level variation using satellite altimetry (see Table 3.1). The effect on measuring local or regional sea level can be even larger. A scale rate error of 0.1 parts per billion per year would cause an apparent sea level change of 0.6 millimeters per year. To put this in context, the mass loss from the Greenland ice sheet is estimated to be on the order of 200 gigatons per year on average over the last few years, corresponding to approximately 0.7 millimeters per year of rise in global mean sea level; Antarctica is losing a similar amount of ice (Velicogna, 2009). Thus, the uncertainty in the observation of sea level change due to errors in the ITRF is currently almost at the same level as the contribution of either ice sheet to sea level rise. Furthermore, there is evidence that the rate at which ice sheets lose mass is increasing by approximately 30 gigatons per year (corresponding to approximately 0.1 millimeters per year increase in sea level rate) (Velicogna, 2009). Improving the ITRF is, therefore, of paramount importance for the study of global sea level rise and its possible acceleration.

BOX 5.1
Defining Precision, Accuracy, Stability, and Drift

The quality of positioning within a reference frame is described in terms of precision, accuracy, stability, and drift:

Precision quantifies the ability to repeat the determination of position within a reference frame (internal precision) and can be measured using various statistical methods on samples of estimated positions. Although precision does not imply accuracy, high precision is a prerequisite for consistently high accuracy and is necessary to resolve changes in position over time. The precision of a reference frame itself (external precision) refers to the variation in the reference frame parameters (origin, orientation, and scale) that arise from statistical variation in the data used to define the frame.

Accuracy quantifies how close a position is to the truth. Strictly, it only applies to absolute physical quantities, such as distance between stations, but this report also uses it to mean accuracy of station position within a reference frame (internal accuracy). Precision contributes to accuracy, but accuracy also takes into account systematic biases arising from calibration errors or imperfect observation models. Accuracy can be assessed if there is a superior measurement technique that can be used as a standard, but since geodesy uses the highest-accuracy techniques, accuracy estimation is not straightforward for geodesy. Accuracy estimates for geodesy therefore typically involve an “error budget” analysis of systematic effects.

Stability refers to the predictability of the reference frame and station positions. The stability of the reference frame refers to the behavior (linearity and consistency) of its defining parameters, and the ability to predict accurately the future positions of the stations that are used to define the frame. That is, the ITRF parameter should not exhibit any discontinuity over the entire time span of the geodetic observations. Furthermore, the ITRF should remain internally consistent even as it is updated from time to time. The stability of a station refers to the ability to predict its future position within the reference frame. For example, local site stability typically implies that all stations at a specific site do not move relative to each other, and the site does not have non-linear motions relative to the ITRF. The deviation of measured station positions from their predicted positions provides information on geophysical processes that were not predicted. Stations of special geophysical interest (for example, for measuring topographic change in the Las Vegas Valley caused by groundwater effects) are obviously not well suited for defining the reference frame, but it is the stability of the frame that allows scientists to detect the interesting and important geophysical effects on the motions of these stations.

Drift refers to relative rotation, translation, and scale between different reference frames, which results in different velocities between stations given in each frame. Drift is a consequence of a lack of stability in one or both of the frames being compared, which in turn may result from systematic error in the measurement techniques, lack of precision in the measurements, or differences in the station motion models.

GEODETIC TECHNIQUES FOR REALIZING THE ITRF

The geodetic techniques that provide measurements for realizing the ITRF are Very Long Baseline Interferometry (VLBI); Global Navigation Satellite Systems (GNSS)/Global Positioning System (GPS); Satellite Laser Ranging (SLR), and Doppler Orbitography Radiopositioning Integrated by Satellite (DORIS). The ground network for each of these geodetic techniques is illustrated in Figure 5.1. These techniques are organized as scientific services within the International Association of Geodesy (IAG) and are integral components of the Global Geodetic Observing System (GGOS) (Plag, 2005; Plag and Pearlman, 2009), which is the IAG’s participating organization in the international Group on Earth Observations. Each of these observational techniques has unique characteristics, strengths, and weaknesses. VLBI provides the orientation of the ITRF relative to the celestial reference frame (i.e., the ‘distant stars’) and is also one of the two techniques currently used for accurately realizing the scale of the ITRF. SLR is used to locate the center of mass of the Earth

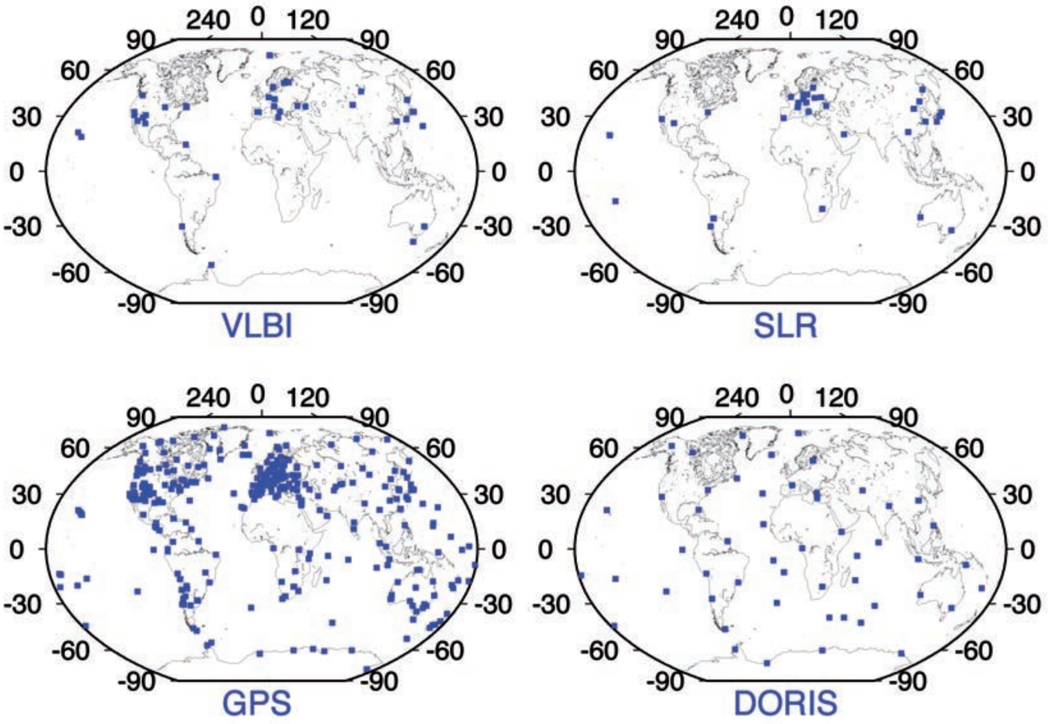

FIGURE 5.1 The network distribution of the four geodetic techniques contributing to the ITRF. Shown are the stations that contributed data during the year 2009. There are thousands of geodetic GPS receivers deployed worldwide, but only a subset of these receivers, coordinated by the International GNSS Service (IGS), are used for the ITRF definition. SOURCE: Courtesy of Zuheir Altamimi, 2010.

system and thereby defines the ITRF origin and contributes to the ITRF scale. GPS contributes the large number of sites that define the ITRF (contributing to its density) and contributes to precise monitoring of polar motion. GPS, DORIS, and SLR are used to position space-orbiting platforms in the ITRF, and GPS is used to position instruments on the Earth's land and sea surfaces (for example, tide gauges and buoys). Locating instruments for two or more techniques near each other at certain ITRF sites (a practice called "co-location") enables connectivity between these techniques.

None of the space geodesy techniques alone is capable of providing all the necessary parameters for ITRF definition (origin, scale, and orientation). Although satellite techniques are sensitive to the center of mass of the entire Earth system (a natural ITRF origin and the point around which a satellite orbits), the VLBI technique is not (its ITRF origin is arbitrarily defined through mathematical calculations). The scale is dependent on the modeling of some physical parameters (such as troposphere or ionospheric refraction), and the absolute ITRF orientation (unobservable by any technique) is conventionally defined through specific mathematical constraints, typically to try to realize no-net or zero-average rotation with respect to the bulk of the Earth's mass. Multi-technique combinations are therefore essential for the ITRF determination.

The most critical ITRF parameters of interest to mean sea level studies in particular, and other investigations in general, are the origin and scale and their long-term stability. For example, any scale bias in the ITRF definition propagates directly to the height component of the stations, and any scale and/or origin bias will directly map to the mean sea level estimation (Beckley et al., 2007). Although SLR currently provides the most accurate realization of the Earth's long-term center-of-mass (the *geo-*

center) for the ITRF origin, estimates of the geocenter location (and its variations owing to seasonal mass redistribution on the Earth's surface, an important geophysical signal in itself) still need to be improved for all the geodetic techniques. Because the ITRF relies on SLR to define its origin and on SLR and VLBI for its scale, the importance of these two techniques for ITRF accuracy and stability over time should not be underestimated. Hence, the problems of scale and origin stability that can particularly affect GNSS/GPS techniques can be overcome by careful alignment to the ITRF, which in turn requires sufficient overlap in networks at co-located sites. Unfortunately, the current SLR and VLBI networks and their co-locations are already poorly distributed and are decreasing over time, posing a threat for the long-term stability of the ITRF. For example, the analysis of the ITRF of 2005 and the pre-2008 analysis showed that the poorly distributed SLR and VLBI networks and scale bias up to 1 part per billion (corresponding to 6 millimeters) and a scale drift up to 0.1 part per billion per year (0.6 millimeters per year). This drift is considerably larger than the science requirement (less than 0.1 millimeters per year) to measure sea level change (see Table 3.1).

Thus, the ITRF is based on information derived from a combination of multiple geodetic techniques. As described in Chapter 4, however, each technique has its own unique targets; VLBI observes quasars, SLR ranges to selected laser geodetic satellites, and GNSS/GPS depends on the navigation satellites. Though this may change in the future, no technique currently contributing to the ITRF has a direct connection to any other technique. Each realizes its own internally consistent set of coordinates, but it is only through local ties at co-located sites that a completely resolved reference frame is realized. As a result, the ITRF quality will suffer from any network degradation over time because it is heavily dependent on the network configuration. The current configuration of co-located sites (in particular, sites with three and four co-located techniques) is far from optimal. The following sections describe the current configuration of co-location sites, including their quality, number, and distribution.

CO-LOCATION SITES

A co-location site is defined by the presence of two or more geodetic instruments occupying simultaneously or subsequently very close locations. These locations must be precisely surveyed in three dimensions, using either classical geodetic methods (usually angles, distances, and leveling measurements between instrument reference points or geodetic markers) or GNSS/GPS (Altamimi, 2005). The national agencies that operate geodetic instruments generally perform least-squares adjustments of local surveys to yield the local ties that connect co-located instrument reference points. Geodetic markers are unambiguous reference points for which geodetic coordinates can be determined. Markers can be either a well-defined physical point anchored in a geodetic monument (such as a pillar or pole) or an instrument reference point (for example, the intersection of axes of an SLR telescope or VLBI antenna, or a GNSS/GPS or DORIS antenna reference point).

Inter-marker distance and accuracy of the local tie are the two main criteria that must be considered for the definition of a co-location site (Altamimi, 2005). Given the need for local tie vectors to be precise at the 1-millimeter level, and considering the increase in atmospheric refraction as a function of increased station separation, the distances between geodetic markers at co-location sites should not exceed 1 kilometer. In addition, repeat surveys of the marker "footprint" are necessary for long-term local tie stability. The current reality, however, is sub-optimal. The poor geographic distribution and insufficient number of co-location sites forces geodesists, for the purpose of the ITRF determination, to consider stations to be co-located even when separated by up to 30 kilometers (for example, the Tidbinbilla/Orroral complex site in Australia). In terms of accuracy, the typical uncertainty of the local ties used for the current ITRF is 2–5 millimeters (sometimes larger than 5 millimeters for the less precise ties). With the increased precision available from geodetic techniques, a precision of 1 millimeter or better should be the goal of all new local tie surveys.

Current Status and Future Requirements of Co-location Sites

At the writing of this report (2010), there are 62 geodetic sites with two techniques, 15 sites with three techniques, and only two sites with all four techniques (see Figure 5.2).[1] One of the two sites with four techniques, the site in Greenbelt, Maryland, includes an old VLBI mobile antenna with very poor performance. Among the 62 two-technique sites, 22 are GNSS/GPS-DORIS co-locations, and DORIS is the third technique in nine of the sites with three techniques. There are only seven sites where VLBI and SLR are co-located, resulting in a very weak connection between these two techniques. In the ITRF construction, GNSS/GPS is now playing a major role connecting both techniques, as all SLR and VLBI sites are co-located with a permanent GNSS/GPS station (Altamimi and Collilieux, 2009). The drawback of this situation is that if there is any GNSS/GPS-related bias, the ITRF-defining parameters would be contaminated (mainly the origin and the scale, as they are determined by SLR and VLBI). One of the major GNSS/GPS weaknesses is the existence of apparent station position discontinuities (which may be up to 5 centimeters in some cases) due to equipment changes (such as changes in the antenna, receiver, or radome) that affect more than 50 percent of the IGS network. Because of these weaknesses and the uncertainties of currently available local ties, the accuracy of the local ties with GNSS/GPS is probably at the level of 4 millimeters in the best cases.[2]

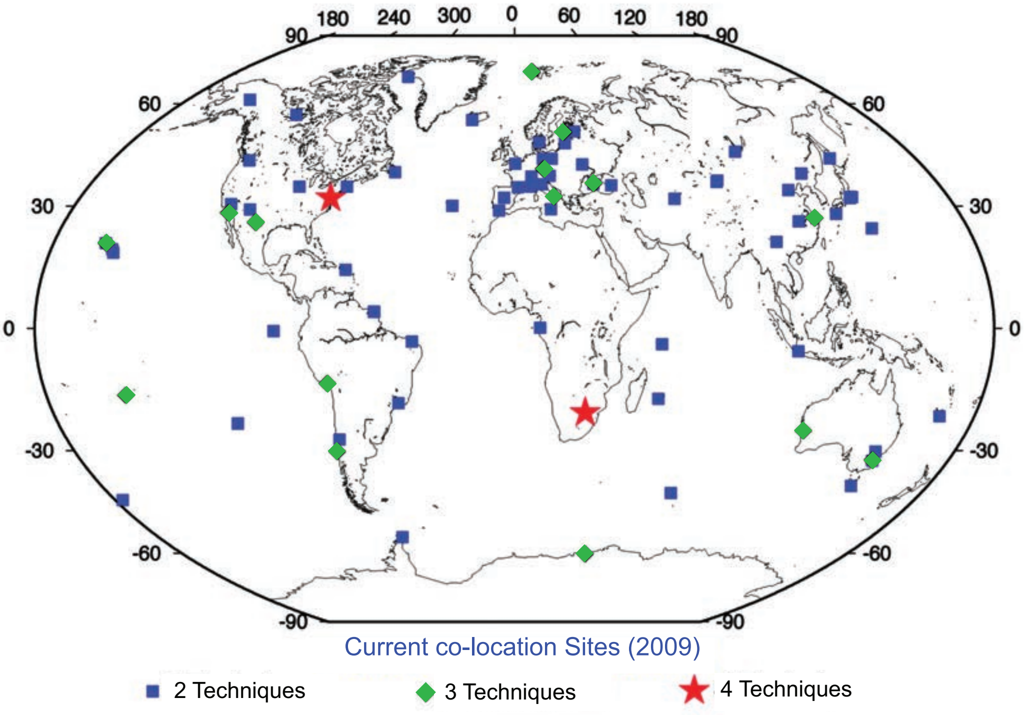

FIGURE 5.2 The current distribution of co-location sites. Only two sites currently have all four geodetic techniques contributing to the ITRF co-located. SOURCE: ITRF Product Center, http://itrf.ensg.ign.fr/.

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[1] ITRF Product Center: http://itrf.ensg.ign.fr/.

[2] Based on the difference between local tie measurements and geodesy estimates, assessed via the Weighted Root Mean Scatter of the tie residuals as results from the ITRF combination (Altamimi et al., 2002, 2007).

The major limitation of a precise local tie is the surveyor's ability to measure the internal geodetic instrument offsets. For example, for a GNSS/GPS-VLBI co-location, the local tie vector consists of the sum of the following three components: (1) the connection from the GNSS/GPS external reference point to the VLBI external reference point; (2) the VLBI internal offsets; and (3) the GNSS/GPS internal offsets. Segment (1) is the tie between the physically accessible points (or markers) that surveyors would normally measure. Segment (2) is the sum of all effects internal to the VLBI observing and data analysis systems that can introduce biases between the point referenced by VLBI data analysts and the external physical reference point used by surveyors. These include any sort of physical deformation of the VLBI antenna structure (due to temperature or the instrument's own weight), especially those that cannot be distinguished from true height displacements or tropospheric refraction effects. Segment (3) is the sum of all effects internal to the GNSS/GPS observing and data analysis systems that can introduce biases between the point referenced by GNSS/GPS data analysts and the external physical reference point used by surveyors. These include direction-dependent errors in the signal propagation model due to antenna or radome effects and near-field long-wavelength multipath biases. The estimated uncertainty for each segment is probably no better than 1–2 millimeters; consequently, the overall error would be at best 3 millimeters for the local tie. Similar uncertainties apply to ties with SLR and DORIS. Consequently, technological innovation is needed to improve the ground-based methods for determining local ties and to regularly monitor the ties for changes.

Although terrestrial techniques might be limited by the uncertainty of measuring instruments' internal offsets, dedicated space missions could provide a prime opportunity for future innovation in this domain. One such space mission currently being proposed by NASA's Jet Propulsion Laboratory (JPL) is GRASP (Geodetic Reference Antenna in Space). GRASP is a proposed micro-satellite mission dedicated to the enhancement of all the geodetic techniques, with potential to improve the definition of the ITRF, its densification, and its accessibility. GRASP proposes to co-locate VLBI, GNSS/GPS, SLR, and DORIS sensors on a well-calibrated spacecraft (for which internal offsets are measured very accurately), to establish precise, stable ties between the key geodetic techniques used to define and disseminate the ITRF. GRASP also offers a potential solution to another difficult problem—the consistent calibration of the myriad antennas used to transmit and receive the signals of existing and future GNSS/GPS infrastructure. Improving GNSS/GPS signal modeling will benefit all precision applications of these systems. For example, simulations at JPL indicate that GRASP would improve by a factor of three the accuracy of orbit determination of GNSS/GPS satellites, of GNSS/GPS positioning, and of GNSS/GPS-based ITRF determination.

ITRF REQUIREMENTS TO MEET FUTURE NEEDS

To achieve the GGOS program goals and support future high-precision geodetic science, the ITRF needs to be robust and stable over many decades. Future scientific objectives drive a target accuracy of 0.1 millimeters per year in the realization of the origin of the ITRF relative to the center of mass of the Earth system (geocenter stability) and 0.02 parts per billion per year (0.1 millimeters per year) in scale stability. Achieving this goal will require improving the geographical distribution of the geodetic techniques, especially SLR and VLBI (GPS and DORIS are already well-distributed), as well as continued investment in the analysis of the data generated by those networks. For example, geocenter stability depends on accurate dynamic modeling and observations of the SLR satellites. Scale stability can be improved by minimizing ranging biases for SLR and better modeling of tropospheric refraction and antenna deformation for VLBI.

The anticipated increase in GNSS/GPS satellites over the next decade suggests the strong potential for GNSS/GPS to contribute to both geocenter and scale stability, but a combination of SLR and VLBI will also continue to be required. Currently, VLBI provides the only stable long-term determination of the orientation of the Earth relative to the stars. SLR and VLBI provide the determination of the ITRF scale, and SLR provides the only determination of the origin. GNSS/GPS and DORIS are improving and may at some point provide comparable contributions to the origin and scale components. The GNSS/GPS scale will be more difficult to improve because it is dependent on the GNSS/GPS satellite antenna phase center offsets. These offsets need to be independently determined, either from pre-launch laboratory testing or more precise modeling of the electromagnetic environment of the satellite-transmitting antennas (assuming that the ITRF scale is already provided by SLR and VLBI), rather than being estimated from the GNSS/GPS data, as is currently the procedure (Schmid et al., 2005). SLR tracking of the GNSS/GPS satellites with retroreflectors can also be used in direct combination to separate orbit and antenna signals, hence it is important to install retroreflector arrays on future GPS satellites. Such arrays are already on the current GLONASS, GIOVE, and COMPASS satellites and are planned for all future Galileo satellites.

In the overall context of the goal to achieve an ITRF tied together at the one-millimeter level, a preliminary study was conducted to scope the size and distribution of the fundamental stations over a global network that would be required (Pavlis, 2008; Pavlis et al., 2008a). A fundamental station for the purposes of this report is a core geodetic ground station with at least one geodetic VLBI telescope; an SLR station (with some stations having LLR capability); at least three GNSS/GPS receivers to provide local tie information and monitor site deformation; a DORIS beacon; terrestrial survey instruments to determine and monitor local ties to the millimeter level; a superconducting or, preferably, an absolute gravimeter; meteorological sensors; and a variety of other sensors, such as seismometers, tiltmeters, and water vapor radiometers (see also Plag and Pearlman, 2009). The initial simulation was limited to considering the contributions of co-located VLBI and SLR stations, because these two techniques together can define completely the ITRF in terms of scale and origin, as well as Earth-orientation parameters (Earth rotation and polar motion). From a well-distributed group of 32 sites that comprise the maximal size network to be examined, three additional experiments considered reducing that network to 24, 16, and 8 sites. The study considered only the SLR from the two current LAGEOS satellites, and the results, illustrated in Figure 5.3, indicate that the ITRF accuracy goals can be achieved with approximately 24 stations. Beyond that number, there is little additional benefit in performance, although additional sites would improve robustness in the case of station outages.

Recommendation. Based on these results, the committee recommends that the United States should work with its international partners to increase the number of multi-geodetic technique sites (particularly co-locating VLBI and SLR), with a goal of reaching a global geodetic network of at least 24 fundamental stations.

While the simulation does not include GNSS/GPS, the inclusion of GNSS/GPS with the co-located SLR and VLBI stations is critical (and easily accomplished) for densification of the ITRF and the propagation of the resulting ITRF to the users, since most users will have access to the ITRF only through GNSS/GPS. Similarly, co-location with DORIS is essential for the most accurate applications of the DORIS technique. It is possible that a more complete simulation that includes the effect of GNSS/GPS may decrease the number of fundamental sites that are needed. Preliminary studies also indicate that SLR tracking to GNSS/GPS satellites can improve considerably the contribution of SLR to the precision of the ITRF, highlighting the importance of including laser reflector arrays on future GNSS/GPS satellites (Pavlis et al., 2009). Inclusion of laser retro-reflectors on GPS Block III satellites has been proposed formally by several U.S. government agencies, and planning and analysis is underway at the time of publication of this report to accomplish this. The

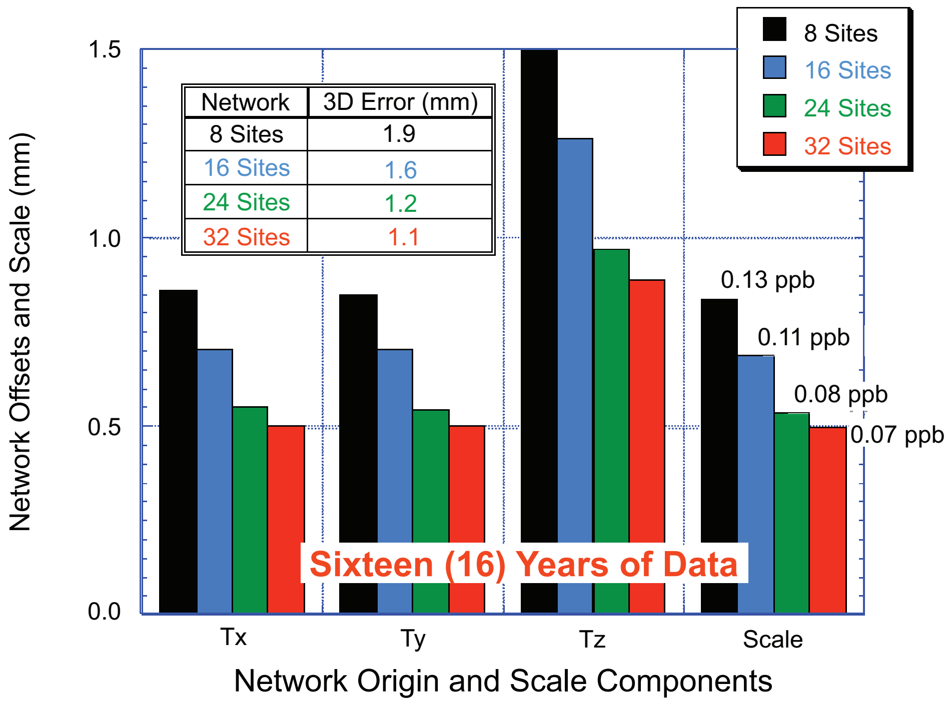

FIGURE 5.3 Estimating the size of the needed global fundamental station network from simulations. As the size of the network is increased from 8 to 32 stations, the accuracy of the determination of ITRF, in terms of origin and scale, is improved, but the improvement is relatively modest with more than 24 sites. This indicates that the ITRF accuracy goals can be largely achieved with approximately 24 stations with co-located SLR and VLBI stations. SOURCE: Courtesy of E. Pavlis, NASA.

reflectors could help specifically to improve the GPS satellite transmitter phase center modeling and to refine orbit modeling.

REGIONAL REFERENCE FRAMES AND THEIR RELATIONSHIP TO THE ITRF

Regional and national geodetic reference systems are essential for a variety of civil, legal, and public safety applications. These systems, however, have been traditionally realized through extensive ground-based surveys, are expected to have significant errors at the national scale (due to the accumulation of error inherent in leveling surveys), and are not always mutually consistent. Since the start of the ITRF development and the advent of improved positioning, however, national geodetic agencies have undertaken significant efforts to redefine and modernize continental and national geodetic systems so that they are compatible with the ITRF. For example, the European Terrestrial Reference System 1989 (ETRS89), the North American Datum of 1983 (NAD83), the Geocentric Datum for Australia (GDA), and other national geodetic systems are linked to the ITRF through conventionally adopted transformation parameters and formulas, and are often defined by fixed coordinates at a given epoch.[3] For example, NAD83 is now defined in terms of a 14-parameter transformation from ITRF96. Regional organizations,

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[3] Epoch refers to a moment in time used as a reference for a model that has time dependence (typically linear).

such as the European Reference Frame (EUREF) and the North American Reference Frame (NAREF), are represented within the IAG structure through their representation in IAG Commission 1. These regional entities play a major role in redefining regional and national datums and their relationship to the ITRF.

From 1987 to 1997, the National Geodetic Survey (NGS), in cooperation with other federal, state, and local surveying agencies, conducted a resurvey of the United States using GPS observations often referred to as High Accuracy Reference Networks (HARNs). Continued improvements in GNSS/GPS technology and requirements from the users of spatial data will eventually require a transition to an improved reference frame based on the ITRF. Positions relative to the ITRF differ from the existing NAD83 by approximately one meter in horizontal position and one meter in ellipsoidal height. NGS already publishes ITRF coordinates for all Continuously Operating Reference Stations (CORS), and will implement, over the next 3–5 years, an adjustment to include the HARNs and other GPS data submitted to NGS.

MODERNIZING THE NORTH AMERICAN DATUM (NAD)

The North American Datum 1983 is a common horizontal reference frame for the North American continent that is legally recognized by the United States and Canada. It is a fundamental element of the National Spatial Reference System (NSRS). Based on the first satellite geodetic results from early Doppler tracking and data from a few VLBI stations in the 1970s, the NAD83 took the North American reference frame into the space age, making obsolete the older NAD27 system that was based on ground-based classical surveys. Twenty-five years later, it would be timely and appropriate to upgrade the NAD system again, taking advantage of the latest global and national geodetic observations and geophysical models. The NAD83 differs from the ITRF at the level of one meter, a very large number considering the approximately one-millimeter level of precision of today's geodetic techniques.

The difficulty for the United States and Canada is that the North American plate rotates, with the result that the coordinates of some stations would change by as much as one meter in 20 years. Fortunately, the rotation of the North American plate is highly stable and is well-understood by geodesists, so the effect of the plate rotation can be taken into account to provide stable coordinates. A NAREF working group of the IAG led by the U.S. NGS and Natural Resources Canada (NRCan) has researched ways to improve the NAD system. The working group, called "Stable North American Reference Frame," is a collaboration between the NGS, NRCan, and university researchers who are experts in the latest geodetic techniques and modeling of geophysical effects. The participation of university researchers had been facilitated by funding from the U.S. National Science Foundation in recognition of the critical need for reference frame improvement for the scientific objectives of the EarthScope program. In addition, the NGS provides a service that enables users throughout the United States to compute the effect of modeled geophysical surface motion as a function of position, a service designed to bring station coordinates to rest after the correction is applied.

The NGS has to work within the legal definition of the NAD83, which was designed before the advent of the GPS in the 1980s. Modern surveyors typically use GNSS/GPS and do not necessarily need to use classical survey markers now that NGS provides data and coordinates from its CORS network. Nonetheless, in most areas, property laws govern the use of ground markers, which should be maintained on that basis. Furthermore, in areas where ground markers undergo large displacements as a result of geological processes, recovery and re-survey of these markers is a precious source of scientific information. The committee recognizes the vision and considerable efforts of NGS in modernizing the NSRS and encourages further developments to modernize the NAD system.

BOX 5.2
Gravity for the Redefinition of the American Vertical Datum (GRAV-D)[a]

NOAA's National Geodetic Survey (NGS) has a federal mandate to provide accurate positioning, including heights, to all federal, non-military mapping activities in the United States. Accurate heights are critical to many scientific endeavors but are particularly important to understanding and protecting low-lying coastal areas, which are subject to flood hazards. In 2007, NGS embarked on the GRAV-D project to determine the gravity-based vertical datum (elevation) with two-centimeter accuracy for much of the country. Because of the fundamental connection between the Earth's gravity field and the definition of height above mean sea level (see Figure 1.2), complete gravity coverage of the continent is needed to connect the geometric height system measured by GNSS/GPS to the physical height system referred to as the geoid. The goal of GRAV-D is therefore to measure the Earth's geoid. "The geoid is theoretical only. You can't see it, touch it or even dig down to find it. Simply put, the geoid is the natural extension of the mean sea level surface under the landmass. We could illustrate this idea by digging an imaginary trench across the country linking the Atlantic and Pacific oceans. If we allowed the trench to fill with seawater, the surface of the water in the trench would represent the geoid. Not a bad way to imagine the geoid, but in reality not something we could easily do" (Natural Resources Canada).[b]

The GRAV-D project consists of three major campaigns:

1. A high-resolution "snapshot" of gravity in the United States will be obtained by a predominantly airborne campaign. The highest-priority targets are the coastline of the continental United States and the American island holdings.
2. A low-resolution "movie" of gravity changes determined by episodic re-visits of absolute gravity sites in an attempt to monitor changes to gravity over time at selected points. Space-gravity missions like GRACE are essential to monitoring changes in the geoid at regional scales.
3. The third component depends on regional surveys where NGS collaborates with local governmental, commercial, and academic partners that are willing to support airborne or terrestrial surveys or to monitor local variations in the gravity field.

[a] National Geodetic Survey (http://www.ngs.noaa.gov/GRAV-D/).
[b] Natural Resources Canada (http://www.geod.nrcan.gc.ca/edu/geod/geoid/geoid02_e.php).

The NGS Gravity for the Redefinition of the American Vertical Datum (GRAV-D) project to modernize the national height system also is related to modernization of the NAD (Childers et al., 2009b; see Box 5.2). In effect, GRAV-D would provide the data necessary to define the national height datum as the new NAD ellipsoidal surface plus a geoid correction, modeled using gravimetric measurements. The combined NAD and geoid correction model would then be part of a new NSRS that would be consistent with the ITRF and also would meet the needs of the most demanding applications, including scientific experiments and monitoring for natural hazards. One aspect of this modernization that the NGS cannot deal with (at least not directly) is the legal definition of the NAD83. Such a radical improvement to the NAD might require Congressional legislation to redefine the national reference system; if that is the case, the committee urges that initiatives to propose such legislation be taken in consultation with the NGS.

6

Support for the Precise Geodetic Infrastructure

In previous chapters, this report outlined how components of the precise geodetic infrastructure interlock to support not only Earth science but also a wide range of applications of benefit to society. Foremost among the benefits is the realization of the International Terrestrial Reference Frame (ITRF), which is determined through the integration of the Very Long Baseline Interferometery (VLBI), Satellite Laser Ranging (SLR), Global Navigation Satellite System/Global Positioning System (GNSS/GPS), and Doppler Orbitography Radiopositioning Integrated by Satellite (DORIS) networks. The ITRF, in turn, provides the foundation for nearly all ground-based and space-based observations in Earth system science and supports a variety of applications, such as land surveying, floodplain mapping, navigation, precision agriculture, and location-based services. As emphasized in Chapter 3, the primary challenge driving advances in geodesy is the study of long-term Earth system processes, such as tectonic deformation, and indicators of global climate change, including sea-level rise and ice sheet melting. While these processes are often imperceptibly slow, they are singularly important to society and simply could not be monitored and understood without the exquisitely precise observations acquired through global geodetic networks. Despite these many applications and its scientific value, many policy makers and members of the general public seem largely unaware of the nation's reliance on the geodetic infrastructure (with the notable exception of GPS) and are therefore reluctant to invest in its maintenance and modernization.

In the United States, geodetic activities are conducted and supported under the aegis of a range of federal science agencies with participation by the national and international academic community. The committee asked representatives of these agencies and the academic community to offer their impressions of the nation's geodetic infrastructure in terms of strengths, weaknesses, opportunities, and threats (Box 6.1). This informal analysis provided a useful framework to address the sustainability of the nation's geodetic infrastructure. The primary conclusion of this analysis is that the geodetic infrastructure has become increasingly fragile as a consequence of delayed replacement of aging components, lack of redundancy with single-point-of-failure designs, imperfect collaboration among contributors, reductions in the trained geodetic workforce due to retirements, and ongoing tightening of operations and maintenance budgets. These factors combined pose a risk of a sudden, drastic loss of geodetic observing capability (see also NRC, 2007c).

BOX 6.1
Informal analysis of strengths, weaknesses, opportunities, and threats of the geodetic infrastructure, as perceived by U.S. agencies

Strengths

- Collaborative initiatives involving multiple agencies and countries.
- Open and transparent data collection, processing, and distribution.
- Ongoing progress and improved performance over multiple decades.
- Major technological advances.
- Collection of accurate global position, satellite orbit, altimetry, and gravity data sets to support research on changes in the Earth system.
- Support of a broad range of groundbreaking societal applications.

Weaknesses

- Lack of clear chain of responsibility and authority for maintenance and development of the nation's geodetic infrastructure.
- Degradation and loss of geodetic stations and satellites.
- Uneven geographic distribution and inadequate co-location of geodetic techniques.
- Lack of satellite data continuity, especially for GRACE and IceSAT missions.
- Systematic technique errors, requiring improvements in technology.
- Inaccessibility of geodetic concepts and terminology.

Opportunities

- Continued scientific and technological advancement.
- Evolution toward geodetic imaging and real-time applications.
- Efficient data transfer from remote stations to central data processing centers, allowing for shorter time intervals and near-real-time solutions.

Threats

- Lack of general awareness and understanding of contributions of geodesy.
- Lack of sustainable, long-term funding due to competing priorities and structure of the federal budget process.
- Perception that current geodetic infrastructure is precise enough.
- Retiring workforce and lack of adequate training for the next generation of geodesists.

Based on its review of prior studies and the scientific literature as well as interviews with members of stakeholder communities, the committee developed a set of recommendations for the maintenance and long-term sustainability of the geodetic infrastructure servicing the full range of existing and future users.[1] These recommendations touch on the national and global fundamental station network,[2] high-precision, real-time GNSS/GPS networks, international collaboration and cooperation, education of the geodetic science workforce, and long-term support of federal geodetic services. These specific recommendations, discussed in the rest of this chapter, all derive from the committee's core recommendation:

> **Recommendation: The United States, to maintain leadership in industry and science, and as a matter of national security, should invest in maintaining and improving the geodetic infrastructure through upgrades in network design and construction, modernization of current observing systems, deployment of improved multi-technique observing capabilities, and funding opportunities for research, analysis, and education in global geodesy.**

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[1] The committee developed no specific recommendation for the proposed GRAV-D project to define a gravity-based vertical datum for the United States, since that proposal is already official policy for NGS and is included in its 10-year plan. However, the committee endorses this concept and notes that it will be an important improvement to the existing national geodetic infrastructure.

[2] A fundamental station includes VLBI and SLR, plus other geodetic systems. See Glossary for full description.

THE GEODETIC INFRASTRUCTURE AND SOCIETY

Implicitly or explicitly, nearly all observations of the Earth system and applications derived from those observations depend on the geodetic infrastructure. This report illustrates that the geodetic infrastructure is critical to the ability to understand and respond to such global issues as climate change and natural hazards, and that its impact also permeates our everyday lives. For example, drivers of cars, airplanes, and boats can now use inexpensive GPS receivers to determine their position to sub-meter precision in real time anywhere on the planet. In the foreseeable future, not only will we be able to know a vehicle's position to centimeter accuracy in real time, but we also may be able to control that position through autonomous navigation systems. Such systems would make possible many tasks offering enormous economic advantages. In addition, future applications of precise geodesy to soil moisture mapping, precise agriculture, transportation systems, and hazard mitigation would have direct economic benefits.

These current and future applications illustrate that the geodetic infrastructure and its related data sets are public goods, in the same sense that national highway systems or weather-prediction services are public goods. Previous National Research Council reports have made the case that raw environmental data are a public good and, as such, should be supported by taxpayers (NRC, 2001). Based on this premise, government agencies have historically covered the costs of building and operating the ground-based networks, observation satellites, and data systems that collect global environmental observations and make them available to researchers and to the public. The long-term support of geodetic equipment, data collection, and data analysis and distribution systems is, in a very direct way, a governmental responsibility that must be incorporated in the permanent mission statements and budgets of relevant state and federal agencies. In addition, because technological progress often arises from research conducted at universities and agencies that are free of any such long-term responsibility, there is a need to systematically transfer technology and expertise gained from geodesy research developments to operational agencies. These agencies must in turn allocate adequate resources and prepare a workforce to take advantage of the geodetic infrastructure and support advanced applications. This is especially true of anticipated future advances, such as those described in Chapter 4.

Geodetic capabilities have advanced by about one order of magnitude per decade since the first satellite operations. This rate of progress shows that a level of performance that is "pushing the envelope" today stands a good chance of becoming tomorrow's basic requirement. As discussed in Chapters 2 and 3, many aspects of geodetic techniques, technologies, and data analysis are progressing rapidly today; such trends will likely persist in the foreseeable future. For example, societal applications of geodetic imaging, using active remote sensing tools such as radar and LiDAR with increasing spatial and temporal resolution and improving accuracy, will probably contribute powerfully to this progress.

Recognizing the benefits of the geodetic infrastructure to science and society and considering anticipated future needs and advances, the committee developed both short-term and long-term recommendations, which are discussed in the following sections.

THE NATIONAL AND GLOBAL FUNDAMENTAL STATION NETWORK

Chapter 5 illustrates the critical contribution of VLBI and SLR to the determination of the ITRF. VLBI uniquely defines the orientation of the ITRF in space, while SLR provides the precise tie to the origin of the Earth (the geocenter). Together, these techniques provide the only strong constraint on the ITRF "scale," but both are susceptible to various error sources that need to be controlled. Maintenance of these techniques, therefore, is essential for maintaining the ITRF in order to meet the ever-increasing accuracy demands of current and future geodetic applications. The most effective use of U.S. investments in this equipment, in the context of the global network, would be to upgrade current VLBI and SLR sites that have been occupied for decades, thereby retaining and extending their worth for long-term ITRF determination. An analysis by Pavlis and colleagues (2010) demonstrated that a densification of the global network of combined VLBI and SLR stations from 8 up to 24 stations would yield substantial improvements in the ITRF.

> **Recommendation: In the near term, the United States should construct and deploy the next generation of automated high-repetition rate SLR tracking systems at the four current U.S. tracking sites: Haleakala, Hawaii; Monument Peak, California; Fort Davis, Texas; and Greenbelt, Maryland. It also should install the next-generation VLBI systems at the four U.S. VLBI sites: Greenbelt, Maryland; Fairbanks, Alaska; Kokee Park, Hawaii; and Fort Davis, Texas. Maintaining the long history of data provided by these sites is essential for reference frame stability as we transition between ever-evolving geodetic techniques.**
>
> **Recommendation: In the long term, the United States should deploy additional stations to complement and increase the density of the international geodetic network in a cooperative effort with its international partners, with a goal of reaching a global geodetic network of at least 24 fundamental stations.**

Other countries have recognized the importance of contributing to the global geodetic infrastructure to support the Global Geodetic Observing System initiative, as well as to advance their own national geodetic goals. One example is the AuScope project, funded under Australia's National Collaborative Research Infrastructure Strategy (Coleman et al., 2008). With an investment of $20 million, the project plans a significant increase in Australia's geodetic infrastructure, including three new VLBI telescopes, a VLBI correlator center, four new gravity instruments (including an absolute gravimeter), an upgrade to one of Australia's two SLR stations, a transportable SLR campaign, and approximately 100 new continuously operating GNSS sites (Johnston and Morgan, 2010).

The next generation of fundamental geodetic sites, comprising VLBI, SLR, and other geodetic systems, needs to be designed with several considerations in mind in order to satisfy requirements for ITRF accuracy and stability. All components must be accurately surveyed to provide local ties between techniques. Furthermore, NRC (1991) and Plag and Pearlman (2009) suggest that three or more GNSS/GPS stations be deployed with permanent, stable monuments within 100–1,000 meters of the SLR and VLBI sites so that differences in local site motions are either negligible or easily monitored. Co-locating three GNSS/GPS stations (or more) allows occasional updates of equipment without jeopardizing the continuity of observations. Periodic satellite or airborne InSAR site characterization also would be extremely valuable to ensure that local motions or deformation are well mapped and understood. These considerations are consistent with the International Association of Geodesy's recommendation 4.1, which asks that "the ITRF be maintained and made accessible with an operational core ensuring ITRF with the accuracy, long-term stability, and the level of accessibility required by Spatial Data Infrastructure applications" (Plag and Pearlman, 2009).[3] However, Plag and Pearlman (2009) urge a much expanded network—of 40 fundamental stations—by 2020.

In addition, the committee also recognizes the importance of accurate gravity field measurements in support of space-based positioning techniques. Further, the proposed implementation of a national geoid-based[4] height system, consistent with global gravity models and accurate to 1–2 centimeters,

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[3] See also The GGOS 2020 Recommendations: http://www.iag-ggos.org/activities/ggos2020_recommendations.php. Accessed June 3, 2010.

[4] The geoid is the level surface (a surface of constant gravitational potential) that approximates mean sea level. The height above the geoid is used to define the actual elevation of a point on the land surface. Extending the geoid to land was typically accomplished with ground-based leveling techniques but is now augmented with global gravity field models from space-based techniques. The International Association of Geodesy is initiating a pilot project for the definition and implementation of a unified geoid-based World Height System, but this issue, still under discussion, lies beyond the scope of this report.

requires strong support for gravity satellite missions and a revitalized U.S. terrestrial (ground and airborne) gravity program. Such a program also would support the multiple scientific and civil applications that call for monitoring changes in the gravity field over regional and global scales.

NATIONAL HIGH-PRECISION, REAL-TIME GNSS/GPS NETWORKS

Chapters 2 and 3 of this report discuss various scientific applications that require high-precision, real-time GNSS/GPS networks. The report also identifies new and future applications of societal importance that call for a rapidly sampled (at least one hertz), real-time GNSS/GPS data stream. These include systems that enable autonomous navigation for land, sea, and air vehicles and robotic equipment; precision tracking of aircraft for laser and radar imaging; monitoring of space weather in the ionosphere; early warning for such natural hazards as earthquakes and tsunamis; improved forecasting of extreme weather events; measurement of ground displacement in landslides; and monitoring of critical structures after a natural disaster to inform emergency response efforts.

The Plate Boundary Observatory (PBO) GPS network, a major component of the NSF-led EarthScope program, could serve as the backbone for a national high-precision, real-time GNSS/GPS network. This 1,100-station network, built with uniform high-quality equipment, standards, and monuments, represents a large capital investment. The potential to transition this infrastructure from research to operations at the completion of the EarthScope project presents a unique opportunity for the nation. With long-term maintenance, densification, and upgrades to facilitate tracking of other navigation satellite constellations, the PBO network would serve the dual purposes of providing both a national backbone for high-precision applications and local reference stations for surveyors and local commercial and governmental service providers.

While there is an overlap between the PBO and other geodetic networks (for example, CORS and state networks), most such networks were not built specifically to support precise geodesy, and the lack of deep anchors tying the GNSS/GPS receiver to the ground in these other systems may introduce uncontrolled movements of the receiver relative to the reference system as a result of shallow deformations or temperature effects (see Agnew, 2007). Any GNSS/GPS network built to scientific standards, however, could be joined with the PBO network. One example is the approximately 200-station GPS network operated by the U.S. Geological Survey to monitor seismic and volcanic hazards in the western United States. Present-generation high-quality GNSS/GPS receivers in this and other networks are capable of high-rate sampling and streaming data over the Internet; consequently, many of these sites either already operate in real-time or could be upgraded to do so.

The strategies for densification of a national high-precision, real-time GNSS/GPS network could be responsive to the needs of specific applications. For example, early warning systems for earthquakes and tsunamis would require a more dense station spacing (approximately 20 kilometers apart) along the west coast of the United States. Weather prediction, on the other hand, might only require 50-kilometer spacing but would require expansion offshore to help predict the strength and tracks of hurricanes. In addition to such applications, a national high-precision, real-time network also would meet the needs of scientists conducting long-term research studies. Shared use of a single network with common transmission of data and data archiving would yield significant cost savings.

> **Recommendation: The United States should establish and maintain a high-precision GNSS/GPS national network constructed to scientific specifications, capable of streaming high-rate data in real-time. All GNSS/GPS data from this network should be available in real-time without restrictions (and at no cost or a cost not exceeding the marginal cost of distribution), as well as in archived data files.**

INTERNATIONAL COLLABORATION AND COOPERATION

Chapter 4 of this report describes voluntary international collaborations, such as the International GNSS Service (IGS), which set standards for participation, including those for site documentation and data provenance; oversee data analysis and quality control through analysis centers; and make data and data products freely available to users. From a global viewpoint, data from the IGS supports the GNSS/GPS component of the ITRF by enabling high-accuracy satellite orbit determination and clock calibration. As such, IGS products are a natural starting point for applications requiring the highest accuracies and are routinely used by researchers and by U.S. federal agencies, even by agencies with their own "in house" capabilities (such as the U.S. Naval Observatory and the National Geospatial-Intelligence Agency). For this reason, among others, IGS is a critical asset to the United States' geodetic infrastructure for science and commerce. In addition, its importance as an adjunct to the national high-precision GPS network recommended above cannot be overstated.

A well-distributed geodetic network around the globe leads to higher accuracy and reduces dependence on data from particular stations. Poor geographic coverage leads to lower accuracy and greater dependence on particular sites, which are given undue weight in the solutions. If such stations experience temporary equipment failures, the determination of orbit parameters and the realization of the ITRF can be affected excessively, a problem that is exacerbated by the existence of systematic model errors that become more detrimental as we push to achieve greater accuracies. Stations currently in the IGS network are sparsely distributed in the southern hemisphere relative to the northern hemisphere (see Figure 5.1). To balance the data from stations in the IGS network for the purpose of maintaining the ITRF, it is therefore necessary to select an optimal subset of northern stations while depending heavily on data from all available sites located south of the equator. Consequently, maintaining and upgrading the IGS stations of the southern hemisphere and expanding the southern portion of the network to the extent possible should receive the highest priority by the IGS.

NASA currently supports the United States' contribution to the IGS network, which includes approximately 70 GPS stations both within and outside of U.S. borders. Outside the United States, some of these sites are on U.S. military bases or scientific installations, and some are operated cooperatively with local agencies or universities. Those sites that are co-located with other geodetic systems play a particularly important role in determination of the ITRF. A significant number of these co-located stations are in the southern hemisphere or other areas where the IGS network has poor geographic coverage or is otherwise weak. As a result, eliminating these stations would have unfortunate consequences for the IGS and its contribution to the ITRF.

Given the geographic and temporal gaps in coverage, degrading infrastructure, and potential loss of data continuity for key geodetic observing systems, and given the increased leverage of collaboratively funded efforts, it is in the interest of the United States to make a long-term commitment to a strong IGS network. This commitment includes support for operation and maintenance of a global network of homogeneous, high-quality sites supporting IGS standards within and outside the United States. These sites should be capable of real-time data transmission to support the recommended national GPS network.

In addition to strengthening the global GPS network to enhance the United States' own geodetic infrastructure, playing a leading role in the IGS enables the United States to exert a strong and lasting influence on IGS standards and practices for the global network and IGS products. To sustain this influence, participation by United States investigators in the bureaus, analysis centers, working groups, and projects of the IGS must be supported.

Recommendation: The United States should continue to participate in and support the activities of the international geodetic services (IGS, ILRS, IVS, IDS, IGFS and IERS) by providing long-term support for the operation of geodetic stations around the world and by supporting the participation of U.S. investigators in the activities of these services.

From the beginning of the field of geodesy, U.S. scientists have recognized the benefits of a global infrastructure and the need for international collaboration. Indeed, the spectacular progress in geodesy over the past half century has benefited greatly from the initial and continued U.S. leadership. Scientists and engineers from many nations now contribute to geodesy to the extent that no individual national contribution—including that of the United States—can be withdrawn without a visible impact. U.S. participation in international coordinating organizations has served the national geodetic community well by creating opportunities for leadership and global collaborations.

The United States' utilization of a robust global geodetic infrastructure directly benefits numerous commercial, military, and scientific applications. Sustaining U.S. participation in international coordinating organizations is therefore important, even from a narrowly national point of view, because the infrastructure supported by these organizations supports a wide range of domestic uses and applications. Much of the success of international collaborations relies on the commitment of volunteer participants, typically scientists and engineers, with support from governments. Although this system has served the scientific community and the general public well, there remains a persistent danger that competing priorities could pose a risk to the continued global operation of the geodetic infrastructure.

Specifically, a long-term national commitment to the primary global geodetic product—the ITRF—would by *de facto* imply a long-term commitment to the geodetic infrastructure, which is needed to ensure the continuity and stability of the ITRF and the many geodetic observing systems that depend on it.

Recommendation: The United States, through the relevant federal agencies, should make a long-term commitment to maintain the International Terrestrial Reference Frame (ITRF) to ensure its continuity and stability. This commitment would provide a foundation for Earth system science, studies of global change, and a variety of societal and commercial applications.

The committee also endorses the Global Geodetic Observing System (GGOS), a component of the Global Earth Observation System of Systems (GEOSS), being built under the aegis of the Group on Earth Observations (GEO), a voluntary partnership of governments and international organizations of which the United States is a leading member. GGOS links together existing and planned observing systems around the world and promotes common technical standards so that data from all these systems can be combined into coherent data sets. GGOS was conceived and introduced by the International Association of Geodesy as the new paradigm for sustained international cooperation toward integrating space-based geodetic techniques. The maintenance and development of the global precision geodetic infrastructure is recognized by GEO as a cross-cutting activity that affects many aspects of Earth science and the lives of most inhabitants of the planet.

AN EDUCATED GEODETIC SCIENCE WORKFORCE

The committee found that one of the "weakest links" in the implementation of a precision geodetic infrastructure was a lack of trained workforce to develop and maintain the infrastructure in the coming decades. Skilled workers are needed to obtain the highest level of accuracy from the infrastructure, assess the capabilities of the infrastructure as it continues to evolve, and capitalize on advances in technology to improve the accuracy of (or decrease the cost of) the infrastructure. As highlighted in the informal analysis summarized in Box 6.1, representatives from every federal agency that spoke with the committee raised concerns about a growing deficit of well-trained space geodesists and engineers with this necessary knowledge. As a science, geodesy has long been a niche discipline, populated by a small group of experts. Agencies are finding it difficult to replace these highly skilled geodesists as they retire and instead are forced to hire young professionals from other disciplines, such as physicists, whom they must train on the job. Alternatively, U.S. agencies can tap into students educated abroad in countries with strong programs in geodesy.

Many American geodesists were trained and supported by the NASA Crustal Dynamics Project (CDP) and the Dynamics of the Solid Earth (DOSE) investigation of the 1980s and early 1990s. These projects focused on addressing important geophysical problems using the nascent geodetic techniques of VLBI, SLR, GPS, and radar altimetry. To achieve the goals of the CDP and DOSE, NASA supported fundamental geodetic research and the training of a generation of graduate students. Today, geodetic tools pioneered by NASA are routinely used in a wide range of Earth sciences. As NASA's focus moved from technique development to science applications in the late 1990s, however, opportunities for graduate training in geodesy diminished. Although many NSF-supported efforts (for example, the EarthScope program) rely on these precise geodetic tools, NSF also does not at the moment have a program that specifically targets fundamental geodetic research.

One of the recommendations of the National Research Council report *Rising above the Gathering Storm* is particularly relevant to the need for a trained geodetic workforce: "Sustain and strengthen the nation's traditional commitment to long-term basic research that has the potential to be transformational to maintain the flow of new ideas that fuel the economy, provide security, and enhance the quality of life" (NRC, 2007c). The past decade has seen the emergence of exciting new geodetic imaging techniques and rapid positioning methods. These advances have the potential to address a host of new scientific questions and applications. The development of these emerging technologies in the United States requires long-term support for fundamental research and training for the next generation of geodesists.

Although the committee did not collect quantitative demographic data about the geodesy workforce, the anecdotal evidence presented to the committee is sufficient to bring the issue to the fore.

Recommendation: A quantitative assessment of the workforce required to support precise geodesy in the United States and the research and education programs in place at U.S. universities should be undertaken as part of a follow-up study focused on the long-term prospects of geodesy and its applications.

NATIONAL GEODETIC INFRASTRUCTURE: A MATTER OF COLLABORATION

Even a cursory examination of the scope of responsibilities assigned to the various agencies that contribute to the national geodetic infrastructure reveals a complex bureaucratic structure, which might be streamlined and clarified with considerable benefit to the nation. The U.S. geodetic infrastructure is dispersed and has not previously been considered holistically. It consists of: (1) interdependent precise geodetic techniques (mainly VLBI, GNSS/GPS, and SLR, but also gravity, altimetry, and geodetic imaging); (2) standards for data acquisition, archiving, and distribution; (3) a geodetic reference system (the North American Datum of 1983); (4) analysis that combines the data sets to create the ITRF; (5) other derived data products (including, but not limited to, atmosphere, ionosphere, and local reference frames); and (6) mechanisms enabling access to those data products. This geodetic infrastructure is a shared national asset that is required for the nation to maintain its global leadership in economic and scientific spheres and to sustain national security. A number of governmental agencies (including NASA, NOAA, DoD, NSF, and USGS) utilize, govern, and support portions of the nation's geodetic infrastructure; in addition, they each depend on the global geodetic infrastructure. Each has independent missions and requirements, however, and there is no clear chain of responsibility (or authority) for maintaining, upgrading, and augmenting the geodetic infrastructure.

Cooperation between and within national agencies and international services is essential to ensure the long-term viability of the global geodetic infrastructure. Fortunately, the discipline of geodesy offers a conceptual framework that has proven successful on a global scale and that could be adapted to satisfy national needs.

> **Recommendation: The United States should establish a federal geodetic service to coordinate and facilitate the modernization and long-term operation of the national and global precise geodetic infrastructure to ensure convenient, rapid, and reliable access to consistent and accurate geodetic data and products by government, academic, commercial, and public users.**

The essential functions of a federal geodetic service would include:

- Maintaining, upgrading, and augmenting the geodetic infrastructure.
- Coordinating the scientific requirements and applications across stakeholders, including federal and state agencies, the scientific community, and commercial and public users.
- Selecting a primary provider and clearinghouse agent for data products, such as raw instrumental data, tracking data, and the necessary metadata.
- Coordinating the production and dissemination of data products, especially when the utilization of identical products by most or all end-users would be demonstrably beneficial or, in some instances, critical (for example, orbit information for precise navigation).
- Supporting emerging geodetic technologies, such as geodetic imaging, and developing the associated tools and data sets to support these technologies.
- Fostering fundamental research and education focused on technological and theoretical developments, ongoing deployments, and novel uses of geodetic infrastructure.
- Functioning as the lead U.S. partner in the deployment of global infrastructure and international services.

The concept of a federal service is nothing new (consider, for example, the National Weather Service), and neither is the concept of multi-agency coordination. The reason for invoking this concept in the context of geodesy is the enormous surge in demand by all stakeholders, which is expected to continue to increase in the foreseeable future. In developing its concept of a federal geodetic service, the committee considered the role and function of the National Executive Committee on Space-based Positioning, Navigation, and Timing (PNT). Although PNT delivers basic and essential administrative coordination at the national policy and agency level, it is not currently charged with coordination of activities at the data product level, nor is it charged with orchestrating the community to ensure an orderly and effective development and promotion of data and data product standards. Thus, the federal geodetic service is needed to provide a centralized access point for accurate, consistent geodetic information for government, academic, and commercial users through state-of-the-art technology, such as Internet portals. This geodetic information would include (but would not be limited to):

- Satellite orbits (for GNSS/GPS, altimetric, or other geodetic satellites);
- Time-dependent station positions;
- Earth rotation and orientation parameters; and
- Time-dependent topography, gravity field, and geoid information.

The concept of a federal geodetic service does not supersede the current missions and strategic plans of the many agencies that contribute to the geodetic infrastructure. Instead, it would remain consistent with, complement, and facilitate these missions.

Reflecting previous recommendations, the action items of a federal geodetic service for the operation and modernization of the geodetic infrastructure should include:

- upgrading the United States' components of the SLR and VLBI networks, and processing the data from these networks to a level of accuracy equal to or surpassing current best performance;
- constructing scientific-quality GNSS/GPS sites throughout the United States, converting CORS sites to PBO standards of accuracy and stability where necessary and practicable; and
- transitioning PBO stations from research to operations upon completion of the NSF- funded EarthScope experiment.

In addition to these previously described recommendations, the committee also recommends the federal geodetic service take on coordination and supervisory roles to ensure that all stakeholders adopt common standards and common data products, and that these products are generated and distributed using the most efficient, state-of-the-art mechanisms available.

Many approaches could satisfy these requirements for a federal geodetic service, all of which have both strengths and weaknesses. Possibilities include:

- **Lead agency:** A specific agency is assigned the lead responsibility and the necessary resources to head the federal geodetic service. This approach takes advantage of agency expertise and funding, but may be complicated by interagency competition.
- **Embedded organization:** The federal geodetic service activities are consolidated into a new organization housed within one of the existing agencies. This approach could offer a more holistic approach. Precedents and possible models include the National Weather Service and the National Biological Survey. However, funding for the long-term support of the infrastructure might decline sharply unless the budget is protected.
- **Multi-agency federal service:** A formalized, comprehensive structure is established whereby the work of the federal geodetic service is carried out mainly by participating agencies, with clearly spelled-out areas of responsibility and authority. The federal geodetic service would have small staff of its own, with participating agencies operating under an interagency agreement to develop, deploy, and operate the infrastructure and coordinate the product generation and dissemination activities. This concept offers the same advantages as the "lead agency" approach, but with a more holistic outlook. On the other hand, the cost would have to include strategic planning. This approach could follow the model of some of the successful international services described in Chapter 4.

It is important that the federal geodetic service take advantage of the existing talent and expertise in federal and state governmental agencies, research organizations, academia, and industry. In order for such a service to succeed and be sustainable, innovative, and flexible, it is imperative that its staff be steeped in state-of-the-art scientific research in precise global geodesy. For this purpose, all agencies that support scientific research in this field (for example, DoD, NASA, NOAA, NSF, and USGS) ideally would provide input to the strategic plan of the service. Periodic independent advice from stakeholders in the public and private spheres and those operating at the local and global level would ensure that the service continues to provide reliable access to accurate geodetic information.

CONCLUSION

The development and deployment of a global precise geodetic infrastructure over the last several decades not only represents a scientific and technological tour de force, but has truly been a classical case of disruptive technology. We cannot imagine our society returning to the days of sextants, spirit levels, and star navigation. Instead, we can imagine autonomous vehicles moving safely at high speed within inches of other vehicles, as well as real-time images of inflating volcanoes or seismic waves rippling across continents. With clocks onboard satellites synchronized with Earthbound clocks to one part in a trillion, we will enable practical uses of general relativity for innumerable scientific and everyday purposes. Because we have yet to explore the applications of much higher spatial and temporal geodetic resolution, we can also expect new science to emerge from a healthy, stable, and well-maintained infrastructure. This report's recommendation for a new federal geodetic service is aimed at facilitating, and perhaps accelerating, such progress. Finally, if the history of similar services is any guide, it can be anticipated that a federal geodetic service would immediately feed into economic activity, provided that users can safely assume an implied long-term, stable operation in support of the geodetic infrastructure.

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Appendixes

Appendix A

Biographical Sketches of Committee Members and Staff

COMMITTEE MEMBERS

J. BERNARD MINSTER (Chair) is professor of geophysics at the Institute of Geophysics and Planetary Physics (IGPP) of the Scripps Institution of Oceanography, University of California, San Diego, and senior fellow at the San Diego Supercomputer Center. Dr. Minster's research interests focus on imaging the Earth's upper mantle and crust using broad-band seismic data and space-geodetic techniques; the latter is by using synthetic aperture radar (SAR) and laser altimetry. He is a member of the ICESat science team, which uses the GLAS instrument to measure ice-sheet mass balance and global topographic change. He has been Principal Investigator on several proposed SAR missions in low Earth orbit, and on a proposed laser altimetry mission to Europa. He was the Nordberg Lecturer at NASA/GSFC in 1996, and was elected a fellow of the American Geophysical Union in 1990. He is the chair of the recently created Earth and Space Science Informatics focus group of the American Geophysical Union. Dr. Minster has chaired numerous NRC committees, including the Committee on Geodesy, the Committee on Geophysical and Environmental Data, as well as seven panels established to review distributed active archive centers, and he has served on numerous committees related to solid earth geophysics. He is currently vice-chair of the World Data Center (WDC) Panel of the International Council for Science (ICSU). Dr. Minster received his Ph.D. in Geophysics from the California Institute of Technology in 1974.

ZUHEIR ALTAMIMI is head of the terrestrial reference systems research group at the Laboratoire de Recherche en Géodésie of the Institut Géographique National (IGN), France. He is also a member of the International Earth Rotation and Reference Systems Service (IERS) Directing Board and of the Governing Board of the International Laser Ranging Service (ILRS). He was elected President of Commission 1 (Reference Frames) of the International Association of Geodesy (IAG) for the period 2007–2011, and he is head of the International Terrestrial Reference System (ITRS) Product Center of the IERS. His principal research focus is the theory and realization of terrestrial reference systems. His honors include Prix de Cartographie de l'Académie des Sciences and Chevalier dans l'Ordre des Palmes Académiques, and he is a fellow of the International Association of Geodesy. He received his Ph.D. in space geodesy from Paris Observatory, and his habilitation (2nd doctorate) from Paris University VI.

GEOFFREY BLEWITT is a research professor with joint appointments at the Nevada Bureau of Mines and Geology and the Seismological Laboratory of the University of Nevada, Reno. Previously, he was a professor in the Department of Geomatics at the University of Newcastle upon Tyne, England. Dr. Blewitt's research focuses on space-based geodesy and the application of very high precision GPS to earth science. Dr. Blewitt is a fellow of the American Geophysical Union and the International Association of Geodesy. He received his B.Sc. in physics from Queen Mary's College of the University of London and his Ph.D. in physics from the California Institute of Technology.

WILLIAM E. CARTER is an adjunct professor in the Department of Civil and Coastal Engineering at the University of Florida and a professor in the National Center for Airborne Laser Mapping (NCALM). Dr. Carter's current research interests focus on the use of advanced geodetic techniques to monitor the time variations of the orientation, gravity and topography of the Earth with sufficient accuracy to refine and discriminate among earth models and geodynamical theories. Dr. Carter previously held a range of positions at NOAA, including chief of the Geoscience Laboratory, chief of the Advanced Technology Branch, and chief of the Gravity, Astronomy, and Space Geodesy Division of the National Geodetic Survey. Dr. Carter received his B.S. in Civil Engineering from the University of Pittsburgh, his M.S. in Geodetic Sciences from the Ohio State University, and his Ph.D. in Civil Engineering from the University of Arizona.

ANNY CAZENAVE is a Senior Scientist at the Laboratoire d'Etudes en Géophysique et Océanographie Spatiale and Centre National d'Etudes Spatiales, Toulouse, France. Her research interests include satellite geodesy and applications to solid Earth, observation and climatic causes of sea level change, and large-scale land hydrology. Dr. Cazenave's recent past and present international responsibilities include memberships on the Earth Sciences panel of the European Research Council, on the scientific panel of GGOS (Global Geodetic Observing System), and on the IPCC Working Group I (as lead author for Ocean climate and sea level; 2004–2007). She is past International Secretary of the American Geophysical Union (2002–2006), and past president of the geodesy section of the European Geosciences Union (1999–2004). Dr. Cazenave is a fellow of the American Geophysical Union, member of the French Academy of Sciences, and a foreign member of the U.S. National Academy of Sciences.

HERB DRAGERT is a senior research scientist with the Geological Survey of Canada and also holds an adjunct professor position with the School of Earth and Ocean Sciences at the University of Victoria. His principal area of research has been the study of crustal deformation within active seismic areas on the west coast of Canada using geodetic techniques such as leveling, precise gravity, laser-ranging trilateration, and GPS. Under his direction, the Geological Survey of Canada established the Western Canada Deformation Array, the first continuous GPS network in Canada for the express purpose of monitoring crustal motions. Data from this network provided the key information which led to the discovery of slow earthquakes and "Episodic Tremor and Slip" in the Cascadia Subduction Zone. Dr. Dragert led Canadian involvement in the Plate Boundary Observatory under the EarthScope Program, which has resulted in more intensive crustal deformation monitoring along the Cascadia Subduction Zone. He served on the UNAVCO Board of Directors from 2003–2006 and he was the Canadian Geophysical Union's J. Tuzo Wilson medalist for 2007. Dr. Dragert received his B.Sc. in mathematics and physics from the University of Toronto and his M.Sc. and Ph.D. degrees in geophysics from the University of British Columbia.

THOMAS A. HERRING is professor of geophysics in the Department of Earth, Atmospheric, and Planetary Sciences at the Massachusetts Institute of Technology in Cambridge. Dr. Herring's research includes using Very Long Baseline Interferometry (VLBI) and global positioning system (GPS) data to develop geophysically-based models of changes in rotation of the Earth and global deformations; developing kinematic models of deformations in California and Central Asia; and developing improved models and analysis systems for VLBI and GPS. He has served on numerous NRC committees, including the U.S. National Committee for the International Union of Geodesy and Geophysics, the Committee on Geodesy, and the Committee on Earth Gravity from Space. He is a fellow of the American Geophysical Union, a fellow of the International Association of Geodesy, and he was the European Geophysical Union's Vening-Meinesz Medalist for 2007. Dr. Herring received his B.Sc. and M.Sc. degrees from the University of Queensland and his Ph.D. in Earth and Planetary Sciences from MIT.

KRISTINE M. LARSON is a professor of aerospace engineering sciences at the University of Colorado, Boulder. Dr. Larson's research focuses on using high precision GPS techniques to address a range of geophysical issues that include measuring and interpreting crustal deformation as well as developing new techniques, including measuring soil moisture. She has studied plate boundary zone deformation in Alaska, Nepal, Tibet, Ethiopia, California, and Mexico. Dr. Larson's research has also emphasized engineering development by pushing the temporal sampling of GPS to subdaily intervals. She served as editor for *Geophysical Research Letters* from 2001-2004. Dr. Larson received her A.B. in Engineering Sciences from Harvard and her Ph.D. in Geophysics from the Scripps Institution of Oceanography, University of California, San Diego.

JOHN C. RIES is a senior research scientist at the Center for Space Research at the University of Texas at Austin. His research interests include orbit mechanics, geodesy, relativity, and the application of computers and computational techniques to the solution of problems in those areas. He has worked with laser range, altimeter, and Doppler data from numerous satellites including LAGEOS-1/-2, Starlette, Stella, Ajisai, SeaSat, ERS-1/-2, SPOT-2, TOPEX/POSEIDON, and Jason-1. His current research efforts are focused on improving gravity model determination for the Gravity Recovery and Climate Experiment (GRACE) and reference frame determination from laser ranging data. He is a member of the International DORIS Service Governing Board and the Gravity Probe-B Science Advisory Committee. He is a fellow of the International Association of Geodesy and a recipient of the NASA Exceptional Technology Achievement Medal. He received his B.S. and M.S. degrees in mathematics from Michigan Technological University in Houghton, Michigan, and his Ph.D. from the Department of Aerospace Engineering and Engineering Mechanics at the University of Texas at Austin.

DAVID T. SANDWELL is professor of geophysics at Scripps Institution of Oceanography (SIO), the University of California, San Diego. Dr. Sandwell's research focuses on using satellite altimetry to analyze marine gravity anomalies, predict and measure seafloor topography, and the development and application of synthetic aperture radar interferometry (InSAR). Prior to his appointment at SIO, Dr. Sandwell was a research scientist at the University of Texas at Austin, and a research geophysicist at the National Geodetic Survey. He is currently chair of the Western North America InSAR Consortium. Dr. Sandwell was the 2004 George P. Woollard Awardee of the Geological Society of America. He is a fellow of the Geological Society of America and the American Geophysical Union. Dr. Sandwell has served on a numerous NRC committees, including the Committee on Geodesy, the U.S. National Committee for the International Union of Geodesy and Geophysics, and the U.S. Geodynamics Committee. He received his B.S. from the University of Connecticut, his M.S. and his Ph.D. in geophysics and space physics from the University of California, Los Angeles.

JOHN M. WAHR is professor of physics at the University of Colorado, Boulder. He is also a fellow at the Cooperative Institute for Research in Environmental Studies at the University of Colorado and Distinguished Visiting Scientist at the Jet Propulsion Laboratory in Pasadena, California. Dr. Wahr's research is focused on time-variable gravity and its earth science applications, the geological and geophysical applications of InSAR, and numerous climate related areas. He has previously served on the NRC's Committee on Earth Studies. Dr. Wahr was awarded the Vening Meinesz Medal in 2004 from the European Geosciences Union, and he is a fellow of the American Geophysical Union. Dr. Wahr received his B.S. in physics and mathematics from the University of Michigan and his M.S. and Ph.D. in physics from the University of Colorado.

Liaison from Committee on Seismology and Geodynamics

JAMES L. DAVIS is a Lamont Research Professor and Director of the Geodesy Laboratory at the Lamont-Doherty Earth Observatory of Columbia University. Dr. Davis's research interests broadly involve positional and physical geodesy using space and satellite techniques. These include applications of space geodesy to studies of geophysics, climate change, and remote sensing of the atmosphere, as well as the development and geophysical applications of permanent GPS networks and research and development of technology aimed at the improvement of the accuracy of space geodetic systems. He received his B.S. in physics from Michigan State University and his Ph.D. from MIT. He is member of the NASA GRACE mission science team, an AGU Fellow, and is past President of AGU's Geodesy Section.

NATIONAL RESEARCH COUNCIL STAFF

DAVID A. FEARY is a Senior Program Officer with the NRC's Board on Earth Sciences and Resources. He earned his Ph.D. at the Australian National University before spending 15 years as a research scientist with the marine program at the Australian Geological Survey Organization (now Geoscience Australia). During this time he participated in numerous research cruises—many as chief or co-chief scientist—and most recently was co-chief scientist for Ocean Drilling Program Leg 182. His research activities have focused on the role of climate as a primary control on carbonate reef formation and improved understanding of cool-water carbonate depositional processes.

LEA A. SHANLEY is a Postdoctoral Fellow with the NRC's Board on Earth Sciences and Resources. Prior to this, she served in a Senate office as a Congressional Science Fellow, sponsored by the American Association for the Advancement of Science (AAAS) and the American Society of Agronomy—Crop Science Society of America—Soil Science Society of America. Her research activities at the University of Wisconsin-Madison focused on geography and applied participatory mapping; this research engaged resource-dependent, coastal and tribal communities in the development and application of geospatial technology and remote sensing, and in the adoption of appropriate data policies, to support coastal and comprehensive land use planning, natural resource management, and agriculture. In addition, she served on a leadership team under the Wisconsin State Geographic Information Officer to facilitate the establishment of the Wisconsin Geographic Information Coordination Council.

ERIC EDKIN is a Senior Program Assistant with the NRC Board on Earth Sciences and Resources. He began working for the National Academies in 2009 and has primarily supported the board on a broad array of Earth resources, geographical sciences, and mapping sciences issues.

COURTNEY R. GIBBS is a Program Associate with the NRC Board on Earth Sciences and Resources. She received her degree in graphic design from the Pittsburgh Technical Institute in 2000 and began working for the National Academies in 2004. Prior to her work with the board, Ms. Gibbs supported the Nuclear and Radiation Studies Board and the former Board on Radiation Effects Research.

NICHOLAS D. ROGERS is a Financial and Research Associate with the NRC Board on Earth Sciences and Resources. He received a B.A. in history, with a focus on the history of science and early American history, from Western Connecticut State University in 2004. He began working for the National Academies in 2006 and has primarily supported the board on a broad array of Earth resources, mapping, and geographical sciences issues.

Appendix B

Presentations to the Committee

Meeting 1–April 6-8, 2008

Enablers and Infrastructures
Richard Brancato, U.S. Department of Transportation
U.S. Naval Observatory Prespective
Kenneth Johnston, U.S. Naval Observatory
NSF Support for Geodetic Infrastructure to Facilitate Earth Sciences Research
Russell Kelz, National Science Foundation
Is Space Geodesy Ready for the Challenges Posed by the NRC Decadal Study?
John LaBrecque, National Aeronautics and Space Administration
FAA WAAS Program Overview
Deborah Lawrence, Federal Aviation Administration
The U.S. Space-Based PNT Current Program and Future Trends
Anthony Russo, National Executive Committee for Space-Based Positioning, Navigation and Timing
NGA's Dependence on Global Geodetic and Geophysical Infrastructure
James Slater, National Geospatial-Intelligence Agency
National Requirements for Precision Geodetic Infrastructure
Dru Smith, National Geodetic Survey

Meeting 2–June 11-13, 2008

A Mission to Enhance the Terrestrial Reference Frame
Yoaz Bar-Sever, NASA's Jet Propulsion Laboratory
SLR and Global Reference Frames over the Next Decade
Ericos Pavlis, University of Maryland
The Use of GNSS for Ionospheric Specification and the Impact of the Ionosphere on GPS
Timothy Fuller-Rowell, University of Colorado

The Use of GPS for Earthquake Hazard Response and Research at USGS
Nancy King, U.S. Geological Survey
The Role and Future of VLBI Geodesy
Chopo Ma, National Aeronautics and Space Administration
Geodetic Infrastructure and Sea Level Change
R. Steven Nerem, University of Colorado
NGA's Dependence on Global Geodetic Infrastructure: Emphasis on Gravimetry
Nikolaos Pavlis, National Geospatial-Intelligence Agency
Considerations of a Global Reference System & the U.S. Role
James Ray, National Geodetic Survey
Radio Occultation Observations for Weather, Climate and Ionosphere
Christopher Rocken, University Corporation for Atmospheric Research
Geodetic Infrastructure and Deep Space Navigation
Bobby Williams, KinetX, Inc.

Meeting 5–June 17-19, 2009

NASA Activities in the Development of a Stable and Accurate ITRF for Climate and Geohazards Research
John LaBrecque, National Aeronautics and Space Administration
USGS Recovery Act Projects
William Leith, U.S. Geological Survey
Summary of Future NGA Requirements for Geodetic and Geophysical Infrastructure and Derivative Data and Products
James Slater, National Geospatial-Intelligence Agency
National Geodetic Survey and the NRC Geodetic Infrastructure Network
Dru Smith and Neil Weston, National Geodetic Survey

Appendix C

Glossary

Accuracy—The closeness of an estimated value (that is measured or computed) to a standard or accepted (true) value of a particular quantity. Strictly, it only applies to absolute physical quantities, such as distance between stations, but this report also uses it to mean accuracy of station position within a reference frame (internal accuracy). Precision contributes to accuracy, but accuracy also takes into account systematic biases arising from calibration errors or imperfect observation models. Accuracy can be assessed if there is a superior measurement technique that can be used as a standard, but since geodesy uses the highest-accuracy techniques, accuracy estimation is not straightforward for geodesy. Accuracy estimates for geodesy therefore typically involve an "error budget" analysis of systematic effects.

- **Horizontal accuracy**—The positional accuracy of a dataset with respect to a specified horizontal datum (Maune, 2007).
- **Vertical accuracy**—The positional accuracy of a data set with respect to a specified vertical datum (Maune, 2007).

Advanced Land Observing Satellite (**ALOS)**—A remote-sensing satellite of the Japanese Aerospace Exploration Agency.

Aircraft Laser Mapping (ALM)—Aircraft-borne laser instrumentation (such as LiDAR) for making maps of the Earth's surface.

Altimetry—A technique for measuring the height of the Earth's solid surface, oceans, or glaciers and ice sheets from space (satellite altimetry) or aircraft (airborne altimetry).

Aquifer—A large zone beneath the water table that stores groundwater.

Argo—An array of thousands of drifting floats for taking ocean temperature and salinity profiles.

Autonomous navigation—Vehicular navigation from one point to another without the assistance of a driver (for example, autopilot).

Base Flood Elevation (BFE)—The computed elevation to which floodwater is anticipated to rise during the base flood (also known as a one percent annual chance flood and a 100-year flood) (FEMA, 2003).

Bathymetry—The underwater depth of the ocean floor.

Bench mark—A permanent monument established by any federal, state, or local agency, whose location and/or elevation are referenced to a specified datum.

Carrier frequency—The frequency used by a radio signal to carry information and to which a receiver must be precisely tuned to isolate that signal from the radio signals at other frequencies.

Celestial reference frame—The inertial (un-accelerated) non-rotating reference frame associated with the distant stars.

Co-location—Two or more geodetic techniques or systems occupying simultaneously or subsequently very close locations.

Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC)—A joint Taiwan/U.S. mission providing atmosphere profiles using GPS occultation measurements.

Continuously Operating Reference Stations (CORS)—A NGS-coordinated network of GNSS receivers to support positioning activities throughout the United States and its territories.

Coordinates—A set of N numbers designating the location of a point in N-dimensional space. Horizontal coordinates are two-dimensional coordinates, normally expressed as x, y coordinates, eastings and northings, or longitude and latitude (geographic coordinates).

Coordinated Universal Time (UTC)—A modern continuation of Greenwich Mean Time, the standard "clock time."

Corner cube—A combination of reflecting surfaces that always reflect light parallel to the incoming direction.

Crustal deformation—The deformation of the Earth's crust in response to stress.

Crustal Dynamics Data Information System (CDDIS)—A NASA system for space geodetic data archiving and distribution.

Cryosphere—The Earth's glaciers and ice sheets.

Datum—A set of constants specifying the coordinate system used for geodetic control (i.e., for calculating coordinates of points on the Earth).

- **Horizontal datum (geometric reference frame)**—A geodetic datum specifying the coordinate system in which horizontal control points are located. The North American Datum of 1983 (NAD83) is the official horizontal datum of the United States. For horizontal datums, at least eight constants are needed to form a complete datum: three to specify the location of the origin of the coordinate system, three to specify the orientation of the coordinate system, and two to specify the dimensions of the reference ellipsoid (NRC, 2007b).
- **Mean sea level**—A tidal datum computed as the arithmetic mean of hourly heights observed over a specific 19-year Metonic cycle. Shorter series are specified by name (for example, monthly mean sea level, yearly mean sea level).
- **Vertical datum**—A set of constants defining a height (elevation) system containing a coordinate system and points that have been consistently determined by observations, corrections, and computations. The North American Vertical Datum of 1988 (NAVD88) is the official vertical datum of the United States.

Decadal Survey—The common name for the National Research Council report *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond* (NRC, 2007a).

Deformation, Ecosystem Structure and Dynamics of Ice (DESDynI)—A proposed NASA InSAR and LiDAR mission optimized for studying hazards and global environmental change.

Distributed Active Archive Centers (DAAC)—NASA centers for archiving, documenting, and distributing data from past and current Earth-observing satellites and field measurement programs.

Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS)—A French geodetic technique in which transmitters on the ground communicate with receivers on satellites to provide precise orbit determination required by ocean altimeter satellites.

Drift (1)—Drift refers to effects on the measurements that change with time in a detectable pattern, for reasons unrelated to the phenomenon under study. Detecting a drift is often a useful way to identify a source of systematic errors.

Drift (2)—Drift also refers to relative rotation, translation, and scale between different reference frames resulting in different velocities between stations given in each frame.

Earth gravitational model, 2008 (EGM2008)—The latest high-resolution global geoid height model, released by the NGA in 2008.

Earth orientation—Wobble and nutation of the Earth's rotation axis.

Earth rotation—The rotation of the Earth on its rotation axis. In geodesy, Earth rotation refers specifically to the perturbation of the rotation rate, which leads to variations in the length of day.

Earth tide—Tides in the solid Earth that are analogous to ocean tides, but of smaller amplitude.

Earthquake cycle—The cycle of strain accumulation on faults followed by rapid release during an earthquake.

EarthScope—An NSF program (with the USGS and NASA as partners) aimed at understanding the structure and evolution of the North American continent.

Elevation—The height of a location above some reference surface (such as the geoid). The elevation of a point is normally the same as its orthometric height (see Height).

Ellipsoid, reference—A reference ellipsoid is an ellipsoid of specified dimensions that is associated with a geodetic reference system or a geodetic datum. Coordinates given in this system are said to be "with respect to the reference ellipsoid" (NGS, 2010). Detailed definitions of ellipsoid can be found on the National Geodetic Survey Website: http://www.ngs.noaa.gov/CORS-Proxy/Glossary/xml/NGS_Glossary.xml

Ellipsoid height—See Height.

El Niño-Southern Oscillation (ENSO)—Disturbances in the ocean temperature (El Niño) and atmospheric pressure (Southern Oscillation) with a 3–7 year cycle, having important consequences for global weather and climate.

Envisat—A European Space Agency Earth-observing satellite for gathering information about the Earth's land, water, ice, and atmosphere.

Ephemeris—A table of values, relative to a specified coordinate system, giving the position of objects in orbit as a function of time (plural: ephemerides).

Epoch—A moment in time used as a reference for a model that has time dependence.

Error—In general, the scientific term "error" (as opposed to a simple "mistake") is intended to measure, and sometimes explain, the difference between an observed or calculated estimate of a quantity and the (usually unknown) true value of that quantity. Related terms are provided below. A detailed definition and descriptions of "error analysis" can be found, for instance, on the National Geodetic Survey Website: http://www.ngs.noaa.gov/CORS-Proxy/Glossary/xml/NGS_Glossary.xml

- **Random error**—a statistical quantity that measures how repeated measurements of the same quantity by a single observer or multiple observers yield slightly different results.
- **Systematic error**—the effect on the result of a measurement caused by a flaw in the measuring instrument or the measuring procedure. Systematic errors (labeled as "biases") can be detected by comparing the outcome of measurements made using completely different instruments or experimental procedures. In that case, they usually can be eliminated by applying a correction procedure to the measured values.

Etalon—A Russian family of passive geodetic satellites (Etalon-I and Etalon-II) dedicated to satellite laser ranging.

European Remote Sensing (ERS)—Satellites (ERS-1 and -2) of the European Space Agency that perform a variety of measurements for Earth monitoring.

Floodplain—Any land area that is susceptible to being inundated by water from any source (FEMA, 2003).

Fundamental station—A core geodetic ground station with at least one geodetic VLBI telescope (ideally two), an SLR station (with some stations having LLR capability), at least three GNSS/GPS stations to provide local tie information and monitor site deformation, a DORIS beacon, terrestrial survey instruments to determine and monitor local ties to the millimeter level, a superconducting or, preferably, an absolute gravimeter, meteorological sensors, and a variety of other sensors such as seismometers, tiltmeters, and water vapor radiometers (Plag and Pearlman, 2009).

Galileo—A European Space Agency GNSS system in development.

Geodesy—The science of accurately measuring and understanding the Earth's geometric shape, its orientation in space, its gravity field, and changes in these properties over time.

Geodynamics—The study of Earth's internal forces (dynamics) and their impacts.

Geographic Information System (GIS)—A system of computer hardware, software, and procedures designed to support the capture, management, manipulation, analysis, modeling, and display of spatially referenced data for solving complex planning and management problems (FEMA, 2003).

Geoid—The equipotential (level) surface of the Earth's gravity field, which is the best approximation to global mean sea level extended over the land. The geoid undulates up and down with local variations in the mass and density of the Earth (Maune, 2007).

Gigaton—One billion metric tons. One metric ton is 1000 kilograms, or approximately 2,205 pounds.

Glacial isostatic adjustment (also called post-glacial rebound)—The ongoing deformation of the Earth due to the rapid disappearance of the glaciers that built up during the last glacial cycle.

Glaciology—The science of glaciers.

Global Navigational Satellite System (GNSS)—General term for positioning systems like GPS, GLONASS, Galileo, and COMPASS.

Global Positioning System (GPS)—A satellite-based navigation and positioning system that enables horizontal and vertical positions to be determined (FEMA, 2003); a global navigation satellite system (GNSS) maintained and operated by the United States.

Gravimetry—The measurement of gravity**.**

Gravity (Normal)—Normal gravity is an idealized model of the Earth's gravity, comprised of a simple latitude and height dependence.

Gravity anomaly—A measure of how actual gravity deviates from the idealized value of normal gravity. Maps of gravity anomalies reflect the changes in the Earth's mass distribution, particularly in the crust.

Gravity for the Redefinition of the American Vertical Datum (GRAV-D)—A proposed NGS program to redefine the vertical datum of the United States with greater accuracy using airborne gravimetry.

Gravity Recovery and Climate Experiment (GRACE)—A NASA satellite system for measuring gravity changes on the Earth, caused mainly by the movement of water on or near the Earth's surface.

Group on Earth Observations (GEO)—The intergovernmental coordinating effort to build a Global Earth Observation System of Systems (GEOSS).

Height—The distance, measured along a perpendicular, between a point and a reference surface (for example, the height of an airplane above the ground surface). Also, the distance, measured upward along a plumb line (line of force), between a point and a reference surface of constant geopotential. Height is often called elevation if the reference surface is the geoid.

- **Ellipsoidal height**—The height above or below the reference ellipsoid (the distance between a point on the Earth's surface and the ellipsoidal surface, measured perpendicular to the ellipsoid). Also called geodetic height (NRC, 2007b).
- **Orthometric height (Elevation)**—The height above the geoid as measured along the plumb line between the geoid and a point on the Earth's surface, taken positive from the geoid.

Horizontal Datum—See Datum.

Hydrology—Study of the global, regional, or local movement, distribution, and quality of water.

Ice, Cloud, and Land Elevation Satellite (IceSAT)—A NASA satellite for measuring the elevation of the surface of glaciers and ice sheets.

Ice sheet—A very large body of ice extending across the land surface.

Interferometer—An instrument that measures differences between the phases of two electromagnetic signals originating from a common source that have traversed different paths. The phase differences are measured by combining the two signals. The amplitude of the combined signal is a function of the phase difference between the two signals. The phenomenon of fluctuations in the amplitude of the combined signals in response to phase changes in the input signals is sometimes referred to as interference (NRC, 2007b).

Interferometric Synthetic Aperture Radar (InSAR)—An airborne or spaceborne interferometer radar system, flown aboard rotary or fixed-wing aircraft or space-based platforms, used to acquire 3-dimensional coordinates of terrain and terrain features that are both man-made and naturally occurring. InSAR systems form synthetic aperture images of terrain surfaces from two spatially separated antennae over an imaged swath that may be located to the left, right, or both sides of the imaging platform (NRC, 2007b).

Interlacing—An agricultural technique whereby multiple crops are planted in the same field.

International Atomic Time (TAI)—A high-precision measurement of time as measured by atomic clocks. From the French, Temps Atomique International.

International DORIS Service (IDS)—An international service under the IAG for coordinating analysis and distribution of DORIS data and data products.

International Earth Rotation Service (IERS)—Serves the astronomical, geodetic and geophysical communities by providing data and standards related to Earth rotation and reference frames.

International GNSS Service (IGS)—An international service under the IAG for coordinating analysis and distribution of GNSS data and data products.

International Laser Ranging Service (ILRS)—International service under the IAG for coordinating analysis and distribution of laser ranging (LLR and SLR) data and data products.

International service—One of the geodetic services under the IAG: IAS, IDEMS, IDS, IERS, IGeS, IGFS, IGS, ILRS, IVS, and PSML.

International Terrestrial Reference Frame (ITRF)—The most accurate global reference frame for scientific and other applications.

International VLBI Service (IVS)—An international service under the IAG for coordinating analysis and distribution of VLBI data and data products.

Ionosphere—The layer of charged particles (ions) surrounding the Earth that can affect radio communications.

Ionospheric refraction—The delay and bending of a radiometric signal caused by free electrons in the ionosphere. Similar to the tropospheric refraction caused by the neutral atmosphere, except that the delay and bending are strongly frequency-dependent and are negligible at optical frequencies.

Jason—A series of joint NASA/CNES ocean altimetry missions (Jason-1 and Jason-2).

Laser Geodynamics Satellites (LAGEOS)—A series of NASA and joint NASA/ASI (Italian Space Agency) spherical laser reflecting satellites (LAGEOS 1 and LAGEOS 2).

Leap second—A one-second adjustment to international atomic time (TAI) (to produce Coordinated Universal Time (UTC)) to maintain its synchronization with the solar day.

Length of day—The exact amount of time (nominally 24 hours) it takes the Earth to rotate on its rotation axis; due to motions of mass on and within the Earth, the length of day continuously varies.

Leveling—The process of finding differences of elevation (NRC, 2007b).

Light Detection and Ranging (LiDAR)—An instrument that measures distance to a reflecting object by emitting timed pulses of light and measuring the time between emission and reception of reflected pulses. The measured time interval is converted to distance (NRC, 2007b).

Location-based services—Services (such as might be delivered to a mobile device) that are aware of and utilize the location of the user.

Low-Earth orbiting (LEO)—LEO satellites are used for radio occultation measurements of the atmosphere using GNSS.

Lunar Laser Ranging (LLR)—A geodetic technique in which a laser signal is transmitted from a ground-based station, reflects off specially designed mirrors (retro-reflectors) placed on the moon, and is received back at the station. LLR provides information about the moon's orbit and rotation.

Magma—Molten (melted) rock that is generally beneath the Earth's surface and is occasionally released by volcanoes.

Mass transport—The movement of mass within the Earth systems, including the atmosphere, oceans, cryosphere, and solid Earth.

Mean High Water (MHW)—Mean high water is a tidal datum computed as the arithmetic mean of the high-water heights observed over a specific 19-year Metonic cycle. For stations with shorter series, a comparison of simultaneous observations is made with a primary control tide station in order to derive the equivalent of the 19-year value (see Datums).

Mean sea level—See Datums.

Milligal—A milligal is about one millionth of the standard gravity acceleration on the Earth's surface (one "g" or approximately 9.8 meters per second squared).

Monument or control monument (also called reference mark)—A structure that marks the location of a corner or point determined by surveying; generally, any material, object, or collection of objects that indicates the ground location of a survey station or corner (http://www.ngs.noaa.gov/CORS-Proxy/Glossary/xml/NGS_Glossary.xml).

Monumentation—The practice of marking known horizontal, vertical, gravity, or other control points with permanent structures, such as concrete pedestals and metal plaques. Once surveyed and marked, these monuments can be used for further surveying and for the alignment of land-parcel boundaries and infrastructure. Good monumentation for a geodetic observing site is where the antenna mounting is durable and stable, the site environment has minimal impact on the measurement signal, and the location of the reference point for each instrument can be precisely determined.

National Flood Insurance Program (NFIP)—The federal program under which flood-prone areas are identified and flood insurance is made available to property owners in participating communities (FEMA, 2003).

Navigation—The science of directing or commanding the movement of a vehicle or craft. U.S. government policies dealing with navigation distinguish it from real-time positioning in that navigation also encompasses a safety-of-life component.

Nutation—Small nodding oscillations of the Earth's rotation axis in space.

Occultation—Passing behind another object. COSMIC uses GPS systems to measure the change in radio waves as a satellite sets behind the Earth from the perspective of another satellite, thereby yielding information on the Earth's atmosphere.

One percent annual chance flood—A flood that has a one percent chance of being equaled or exceeded in any given year; also known as a 100-year flood and a base flood (FEMA, 2003).

Orthometric height—See Height.

Plate tectonics—The theory that explains many geophysical phenomena in terms of the motions of plates that cover the surface of the Earth.

Polar motion—The movement of Earth's rotation axis relative to the crust.

Position—The location of a point on the surface of the Earth, expressed in terms of one of several coordinate systems. Examples are geographic position (latitude, longitude, and altitude); Universal Transverse Mercator (UTM) northing, easting, and height; or State Plane northing, easting, and height (NRC, 2007b).

Postglacial rebound—See glacial isostatic adjustment.

Postseismic—Occurring after an earthquake.

Precise orbit determination—The precise determination of the orbital position of a satellite by geodetic methods.

Precipitable water vapor (PWV)—A measure of the total amount of water in the atmosphere.

Precision—A measure of the repeatability of a measurement. In the context of this report, precision quantifies the ability to repeat the determination of a position within a reference frame (internal precision), and can be measured using various statistical methods on samples of estimated positions. Although precision does not imply accuracy, high precision is a prerequisite for consistently high accuracy, and is necessary to resolve changes in position over time. The precision of a reference frame itself (external precision) refers to the variation in the reference frame parameters (origin, orientation, and scale) that arise from statistical variation in the data used to define the frame.

Precision agriculture—Application of geodetic, remote-sensing, and geographical information management technologies to farming.

Preseismic—Occurring before an earthquake.

Quasars—The most distant and luminous objects in the universe; quasars emit radio waves that are used in the geodetic technique of VLBI.

Radar—Radio detection and ranging. An instrument for determining the distance and direction to an object by measuring the time needed for radio signals to travel from the instrument to the object and back, and by measuring the angle through which the instrument's antenna has traveled (NRC, 2007b).

RADARSAT—A series of Canadian remote sensing satellites (RADARSAT-1 and RADARSAT-2).

Radio telescope—Parabolic radio dishes that are used in VLBI.

Radiosonde—Weather balloon.

Reference frame—A set of three-dimensional Cartesian coordinates (x, y, z), and the rates of change of these coordinates over time, for a network of points on the Earth's surface that defines the coordinates for other sites.

Reference system—The theories, models, and physical constants underlying a reference frame.

Remote sensing—A general term for systems that remotely collect data from an aircraft, spacecraft, satellite, buoy, or ship about an object or phenomenon on the surface of the Earth.

Retroreflector—An array of optical corner cubes.

Satellite Laser Ranging (SLR)—A geodetic technique in which a laser signal is transmitted from a ground-based station, reflects off specially designed mirrors (retro-reflectors) placed on satellites, and is received back at the station. SLR provides range tracking data for precision orbit determination of geodetic satellites.

Scale—A parameter that controls the distance between points in a network. In the context of mapping, scale is a number, constant for a given map, which represents the ratios of small distances on the map to the corresponding actual distances.

Sea level—In general, the reference elevation of the surface of the sea from which elevations are measured. This term is used as a curtailed form of mean sea level (see Datum) (NRC, 2007b).

Sea surface height—The spatially and temporally variable height of the sea surface.

Sea surface topography—Sea surface height.

SEASAT—The first satellite designed for remote sensing of the Earth's oceans with synthetic aperture radar.

Shoreline—The boundary line between a body of water and the land, in particular, the boundary line between the water and the line marking the extent of high water or mean high water (Datum) (NRC, 2007b).

Space weather—The environmental conditions in near-Earth space, including the ionosphere.

Stability—Reference frame and station position predictability through time.

Standard—An agreed-upon procedure in a particular industry or profession that is to be followed in producing a particular product or result (NRC, 2007b). Alternatively, a number, or set of numbers, established in an industry, a science, or a technology, setting limits on the precision or accuracy with which operations, measurements, or products are to be made.

Starlette—A passive French satellite, launched in 1975, used in Satellite Laser Ranging, predominantly to measure the gravity field.

Stick-slip—Behavior (often of a fault) characterized by periods of sticking followed by periods of slipping.

Strain—A measure of deformation that occurs (in the Earth's crust, for example) in response to applied forces.

Subduction—The process whereby one of the Earth's tectonic plates flows beneath another plate.

Subsidence—Downward vertical motion of land.

Surface Water Ocean Topography (SWOT)—A proposed NASA/CNES satellite mission to make the first complete survey of Earth's oceans and freshwater bodies.

Synthetic Aperture Radar—A radar containing a moving or scanning antenna; the signals received are combined to produce a signal equivalent to that which would have been received by a larger, stationary antenna (NRC, 2007b).

TOPEX-Poseidon—Joint NASA/CNES satellite altimeter for mapping ocean surface topography.

Topography—The form of the features of the actual surface of the Earth in a particular region, considered collectively; also called terrain (Maune, 2007).

Total Electron Content (TEC)—A measure of the density of free electrons per square meter as integrated along a path traced through the ionosphere, usually measured in TEC units, where 1 TEC = 10^{16} electrons / m^2.

Troposphere—The lowest region of the atmosphere, containing almost all the water vapor.

UNAVCO—NSF- and NASA-sponsored organization that supports geodetic research in the United States.

Universal Time 1 (UT1)—Used to represent the Earth's rotation, this nomenclature is left over from when time was determined by the Earth's rotation rather than by atomic clocks.

Vertical Datum—See Datum.

Very Long Baseline Interferometry (VLBI)—A geodetic technique using large, ground-based, parabolic-dish radio telescopes to observe quasars (the most distant objects in the cosmos). VLBI sites provide information on the Earth's rotation and the direction of the Earth's spin axis.

Wobble—See polar motion.

World Geodetic System 1984 (WGS-84)—The latest version of the DoD World Geodetic System, which is consistent with ITRF at the centimeter level (but the ITRF is more accurate).

Appendix D

Abbreviations and Acronyms

ALM	Aircraft Laser Mapping
ALOS	Advanced Land Observing Satellite
BARD	Bay Area Regional Dense array
BFE	Base Flood Elevation
CDDIS	Crustal Dynamics Data Information System
CDP	Crustal Dynamics Program at NASA
CHAMP	Challenging Mini-Satellite Payload for Geo-scientific Research and Applications Program
CITRIS	Scintillation and Tomography Receiver in Space
CNES	Centre National d'Études Spatiales, the French space agency
COMPASS	Chinese GNSS, currently in development (also known as Beidou)
CONUS	Continental/Coterminus/Contiguous United States
CORS	Continuously Operating Reference Stations
COSMIC	Constellation Observing System for Meteorology, Ionosphere, and Climate
DAAC	Distributed Active Archive Center
DARPA	Defense Advanced Research Projects Agency
DEM	Digital Elevation Model
DESDynI	Deformation, Ecosystem Structure, and Dynamics of Ice
DLR	Deutsches Zentum für Luft-und Raumfahrt
DoD	U.S. Department of Defense
DORIS	Doppler Orbitography and Radiopositioning Integrated by Satellite
DOSE	Dynamics of the Solid Earth
DOT	U.S. Department of Transportation

EDC	EUROLAS Data Center
EGM2008	Earth Gravitational Model 2008
ENSO	El Niño/Southern Oscillation
EOP	Earth Orientation Parameters
EPA	Environmental Protection Agency
ERS	European Remote Sensing
ESA	European Space Agency
ETS	Episodic Tremor and Slip
FAA	Federal Aviation Administration
FEMA	Federal Emergency Management Agency
FGCS	Federal Geodetic Control Subcommittee
FGDC	Federal Geographic Data Committee
GDA	Geocentric Datum of Australia
GDGPS	Global Differential GPS
GPS	Global Positioning System
GEO	Group on Earth Observation
GEOINT	Geospatial Intelligence
GEOSS	Global Earth Observation System of Systems
GFO	GeoSat Follow-on Mission
GFZ	GeoForschungs Zentrum
GGOS	Global Geodetic Observing System
GIA	Glacial isostatic adjustment
GIS	Geographic Information System
GLONASS	Russian GNSS, also known as GLObal'naya NAvigatsionnaya Sputnikovaya Sistema
GMSL	Global Mean Sea Level
GNSS	Global Navigational Satellite System
GOCE	Gravity Field and Steady-state Ocean Circulation Explorer
GPS	Global Positioning System
GR	General Relativity
GRACE	Gravity Recovery and Climate Experiment
GRAIL	Gravity Recovery and Interior Laboratory
GRASP	Geodetic Reference Antenna in Space
GRAV-D	Gravity for the Redefinition of the American Vertical Datum
GRGS	Groupe de Raecherche de Géodésie Spatiale
HARNs	High Accuracy Reference Networks
HF	High Frequency
IAG	International Association of Geodesy
IAS	International Altimeter Service
ICESat	Ice, Cloud, and land Elevation Satellite
IDS	International DORIS Service
IERS	International Earth Rotation and Reference Systems Service
IGFS	International Gravity Field Service
IGN	Institut Géographique National

IGS	International GNSS Service
ILRS	International Laser Ranging Service
IPCC	Intergovernmental Panel on Climate Change
ITRF	International Terrestrial Reference Frame
IVS	International VLBI Service
JERS-1	Japanese Earth Resources Satellite
JPL	Jet Propulsion Laboratory
kHz	kiloHertz
LBS	Location-Based Services
LEO	Low-Earth Orbiting
LiDAR	Light Detection and Ranging
LLR	Lunar Laser Ranging
LoD	Length of Day
MHHW	Mean Higher High Water
MHW	Mean High Water
MIT	Massachusetts Institute of Technology
NAD27	North American Datum of 1927
NAD83	North American Datum of 1983
NAREF	North American Reference Frame
NASA	National Aeronautics and Space Administration
NAVD88	North American Vertical Datum of 1988
NCALM	National Center for Airborne Laser Mapping
NGA	National Geospatial-Intelligence Agency
NGS	National Geodetic Survey
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NSDI	National Spatial Data Infrastructure
NSF	National Science Foundation
NSRS	National Spatial Reference System
OGCMs	Ocean General Circulation Models
PANGA	Pacific Northwest Geodetic Array
PBO	Plate Boundary Observatory
PGR	Postglacial Rebound
PO.DAAC	Physical Oceanography Distributed Active Archive Center
PSMSL	Permanent Service for Mean Sea Level
PNT	Positioning, Navigation, and Timing
POD	Precise Orbit Determination
PWV	Perceptible Water Vapor
SLR	Satellite Laser Ranging
SMAP	Soil Moisture Active and Passive Satellite

SMOS	Soil Moisture and Ocean Salinity Satellite
SNARF	Stable North American Reference Frame
SRTM	Shuttle Radar Topography Mission
STP	U.S. Space Test Program
SWOT	Surface Water Ocean Topography
TAI	International Atomic Time (from the French, Temps Atomique International)
TEC	Total Electron Content
TIGA	GPS TIde GAge bench mark monitoring
TWSTFT	Two-Way Satellite Time and Frequency Transfer
UAV	Unmanned Aerial Vehicle
UCAR	University Corporation for Atmospheric Research
UCSD/SIO	University of California, San Diego/Scripps Institution of Oceanography
UHF	Ultra High Frequency
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
USNO	U.S. Naval Observatory
UTC	Coordinated Universal Time
UT1	Universal Time 1
VLBI	Very Long Baseline Interferometry
VLF	Very Low Frequency
WAAS	Wide Area Augmentation System
WDC	World Data Center
WGS-84	World Geodetic System 1984
WRMS	Weighted Root-Mean Square